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FEASIBILITY AND OPTIMAL MANAGEMENT OF SUPPLEMENTAL SPRINKLER IRRIGATION IN EAST CENTRAL ALBERTA

by

©

BRIAN GLENN MCCONKEY

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

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EDMONTON, ALBERTA
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E. Rapp

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Date April 22, 1985

ABSTRACT

A computer simulation model of weather, soils, plant growth, and irrigation systems was developed to estimate the feasibility of supplemental sprinkler irrigation in east central Alberta. The computer simulation model provided good estimates of crop moisture use and yields in response to water management decisions.

Supplemental irrigation of alfalfa hay was profitable in the Dark Brown soil zone providing all aspects of crop production were well managed, an inexpensive water source was available near the irrigated land, and available moisture in root zone was maintained less than 50% depleted. The major limitation to irrigation development in the Dark Brown soil zone was the limited availability of suitable surface sources of irrigation water. In the Black soil zone, supplemental irrigation of alfalfa hay was a marginal investment. Irrigation significantly reduced the variation in seasonal yields resulting from natural moisture conditions.

Supplemental irrigation of hard spring wheat for grain was not very profitable in the Dark Brown soil zone even if crop production was very well managed. Optimal irrigation management for wheat was to maintain available moisture in the root zone less than 35% depleted. Supplemental irrigation of hard spring wheat in the Black soil zone did not increase net income over that possible from dryland

farming. Irrigated wheat yields were more stable than dryland yields.

The profitable sprinkler irrigation systems were the 400 m long towable centre pivot irrigating two quarter sections and a side roll with two 400 m long laterals irrigating one quarter section. Maximum returns with a 400 m long stationary centre pivot were possible if it was used to make frequent, relatively light applications. Shorter centre pivots and hard hose reel travelers were the least profitable irrigation systems. There was no advantage to using an overextended irrigation system as opposed to a system which could supply crop moisture needs throughout the growing season.

Net returns from irrigation were lowest for soils with a nearly impermeable layer which restricts the rooting zone and downward drainage. When the supply of irrigation water and/or labour were limited, the best irrigation strategies were to maintain only the upper one-half of the root zone moist and to stop irrigation entirely two weeks before the wheat was ready for swathing or two weeks before the second cutting of alfalfa. In east central Alberta, both wheat and alfalfa were most responsive to irrigation during the period from mid-June to early August.

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I wish to express my appreciation to Professor E. Rapp for his advice, encouragement, and moral support throughout this project.

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Finally, I would like to thank Adele for her understanding and optimism during this awesome undertaking.

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1.0 Introduction

Inadequate moisture is the major constraint on crop yields on the Canadian Prairies. Consequently, Prairie farmers have a natural interest in supplemental irrigation. Supplemental irrigation refers to the practice of artificially applying water to supplement rainfall and stored soil moisture.

During the past decade, the cost of farm inputs including land, machinery, fuel, fertilizers, and herbicides has increased more rapidly than the price of farm products. As a direct result, the profit margins in farming are smaller, so that low yields during dry years may spell financial hardship. This is particularly true for a beginning farmer who often must meet large debt payments. Several closely spaced dry years may even bankrupt a farmer. Drought occurs when precipitation is less than that expected by the farmer. Therefore, each farmer will have his/her own idea of the value to place on the capability to eliminate the risk of drought. Supplemental irrigation is one method to help stabilize cash income and reduce the consequences of dry weather.

Crop insurance partially covers the losses to yield due to unusually dry weather. Coverage is based on a fixed percentage of long term normal yields for similar soils in the same area. However, if the farmer applies large quantities of fertilizer and herbicides, the coverage is the same if he/she applied none. Therefore, a farmer who uses relatively large amounts of expensive inputs may not be completely compensated for losses due to insufficient precipitation. Supplemental irrigation ensures that moisture stress will not reduce the return from expensive seed, fertilizer, and herbicides.

Dry weather can reduce forage yields substantially. During a dry year, the quantity of on-farm feed becomes limited while the delivered price of off-farm feed rises. As a result, the cattle producer may be forced to sell part of his/her breeding herd (which may be the result of years of effort to improve herd quality) at slaughter prices. Supplemental irrigation is a practical method to achieve a more assured supply of forage.

Supplemental irrigation can raise the average yield per unit area. Hence, providing the returns from the extra production exceed the costs of irrigation, irrigation can increase net farm income.

The long-term trend has been for farmers to increase their cultivated area. Also many beginning farmers choose to work with their farming parents and therefore would be considering purchasing land near their parents' farm. However, in east central Alberta, the price of farmland has risen substantially during the last 10 years. Moreover, even if the price of farmland is not prohibitive, no farmland may be for sale in the immediate area of interest. By raising average crop yields on an existing parcel of land, supplemental irrigation can be an alternative to buying or leasing farmland.

Irrigation is costly. A farmer considering investing in supplemental irrigation needs the following information: i) how much water is needed for supplemental irrigation; ii) what is the average and the variation of expected crop yields with irrigation; iii) what will irrigation cost; iv) what is the average and the variation of expected returns from irrigation; v) what is the quantity and the timing of labour requirements associated with supplemental irrigation; vi) what is the best type of irrigation system to purchase; vii) what constitutes the best management practice for each type of irrigation system; and viii) how sensitive are the yields and returns from irrigation to system management?

To answer the above questions, many years of extensive irrigation field trials would be required. An alternative to field trials is to simulate crops, soil and the irrigation system with a mathematical model implemented on a high speed computer. This is particularly attractive in east central Alberta because few irrigation trials have been conducted in the past. The principle advantage of computer modeling is that it is less costly than actual experiments. A well validated model can be used to estimate the effects of irrigation for many more years than would be feasible with real field trials. Frequently, after analyzing experimental results, the experimenter has a number of "what if" questions -- i.e. "What if this had been done?", "What if this had occurred?". Using a computer model, questions of this type are easily answered.

The primary concern of the researcher is the validation of the model's performance. A computer model which does not realistically represent the real world is of little value. Consequently, a great deal of preparatory research and model validation must be performed to ensure a computer model is truly simulating real world behavior.

1.1 Objectives

The primary goal of this study was to develop and implement a computer simulation model of weather, crops, soils, and irrigation systems for east central Alberta. This model was to have wide geographical applicability in Alberta as well be sufficiently accurate to represent results which could be expected on irrigated farms with good management. The objectives of the study were to use this model to estimate:

1) the irrigation water requirements,
2) the yearly pattern of irrigated yields,
3) the costs and labour involved with irrigation,
4) the monetary returns possible from supplemental irrigation, and

5) the effects of irrigation system management and seasonal water supply on yields and returns.

Because weather patterns can change significantly over short distances, the weather at three locations in east central Alberta, Coronation, Edmonton, and Lacombe was evaluated. For comparison and validation purposes, weather at Lethbridge in southern Alberta was also analyzed.

Hard spring wheat for grain and alfalfa (or alfalfa-grass mixtures) for hay are important dryland crops in east central Alberta. In addition these are also important irrigated crops on the Canadian Prairies. Finally, wheat and alfalfa represent two distinct types of crops in terms of water needs -- wheat is similar to annuals harvested for their seed which have periods when they are extra-sensitive to moisture stress while alfalfa is similar to other perennial forages which have greater total water requirements than annuals but are not especially sensitive to moisture stress at any time during their growth cycle. Therefore these two crops were chosen for modeling.

The assumption was made that irrigation water would need to be pumped to field level and that labour for irrigation would be limited. With these assumptions sprinkler irrigation becomes an appropriate irrigation method. Three sprinkler irrigation systems were investigated -- side roll, hard hose reel traveler (big gun), and towable and stationary centre pivots.

Three soil types were included in the study -- a medium to fine textured soil without root zone restriction, a coarse textured soil without root zone restriction, and a fine textured soil with a hardpan which restricts root penetration and moisture movement.

2.0 Description of East Central Alberta

2.1 Boundaries

The study area lies between townships 36 and 66, from the Fourth Meridian to range 10 west of the Fifth Meridian. The northern and southern boundaries correspond to east-west lines approximately through the towns of Athabasca and Innisfail, respectively. The study region extends from the Alberta-Saskatchewan border to a north-south line lying 25 km west of Rocky Mountain House.

2.2 Agriculture

The study area includes much of the best land for agriculture, in terms of both soils and natural climate, in Alberta. The area corresponds roughly with the agricultural areas on the north east, north west, and north central regions of Alberta Agriculture. Table 2.1 lists some cumulative agricultural statistics for these regions. The study area contains over half of Alberta farms and accounts for more than half of Alberta's agricultural production. The agricultural economy is diversified involving production of a number of field crops along with a variety of livestock enterprises. A large proportion of

Table 2.1 Selected Agricultural Statistics (1976) for the the North East, North West, and North Central Regions

		% of Alberta
Farms	33 352	57
Farmland		
total ('000 ha)	8 363	44
average farm size (ha)	251	n/a
Land Use ('000 ha)		
hard spring wheat	905	40
other wheat	64	15
barley	1 353	52
oats	370	70
canola	174	50
tame hay	858	64
pasture	919	58
summerfallow	706	32
vegetables	0.77	8
livestock ('000 head)		
dairy cows and heifers	147	67
other cattle	2 036	51
hogs	591	63

Source: Statistics Branch, Agriculture in the North West Region, Agriculture in the North East Region, Agriculture in the North Central Region, Alberta Agriculture, Edmonton.

the feed grains are destined to be fed to livestock on the farm where grown.

2.3 Climate

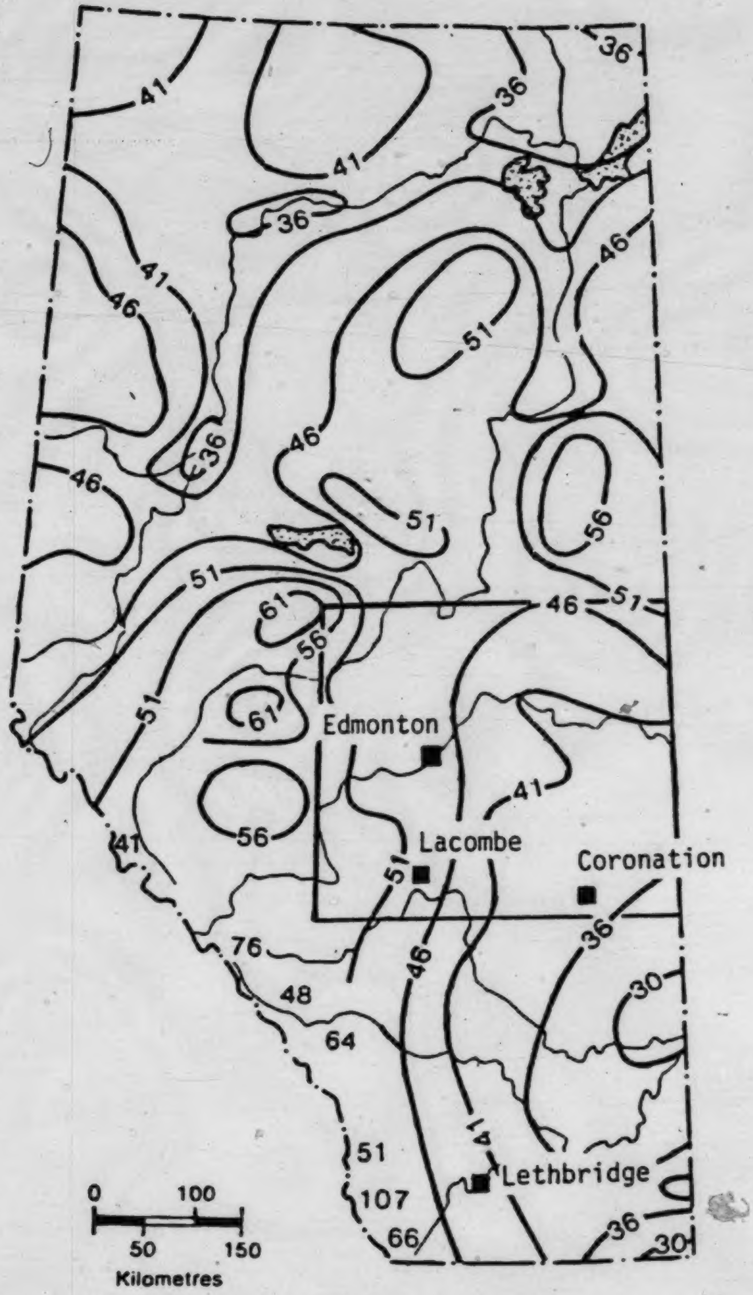
The climate is classed as boreal having long cold winters and short warm summers. Long-term average temperatures in any season decrease moving either northward or eastward. Table 2.2 gives the mean monthly maximum and minimum daily temperatures and mean monthly precipitation for Coronation, Edmonton, Lacombe, and Lethbridge.

Figure 2.1 shows the mean annual precipitation in Alberta with the study region outlined. This figure also shows the location of the sites whose weather was analyzed. Generally mean annual precipitation increases in a northerly or easterly direction. About 65 to 75% of the annual precipitation falls during the growing season. The south eastern portion of the study region is classed as semi-arid. This means that there is normally a moderately severe moisture deficit. Moisture deficit is the difference between atmospheric demand for water and precipitation. The western edge and northwestern corner of the region are classed as humid to subhumid -- i.e. little to significant yearly moisture deficits. The remainder is primarily subhumid which has significant annual moisture deficits.

Table 2.2 Mean Monthly Daily Maximum and Minimum Temperatures (°C) and Mean Monthly Precipitation (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
							Coronation					
Tmax	-11.6	-6.6	-2.0	8.8	16.9	20.9	24.0	22.9	17.0	11.2	0.2	-6.9
Tmin	-21.3	-16.8	-12.1	-2.9	3.5	8.0	10.5	9.2	4.0	-1.7	-10.1	-16.8
Precip	21.5	17.1	20.7	23.0	36.0	57.6	63.0	51.6	32.7	15.0	15.0	19.6
							Edmonton					
Tmax	-10.9	-5.6	-0.9	9.3	17.2	20.8	22.4	21.5	16.5	11.4	-0.1	-7.5
Tmin	-22.0	-17.1	-12.4	-2.9	3.0	7.3	9.2	8.1	3.1	-2.1	-10.9	-18.5
Precip	24.4	17.6	16.0	20.2	42.4	76.7	91.6	78.2	45.7	15.4	16.7	21.9
							Lacombe					
Tmax	-10.0	-4.4	0.0	9.3	16.9	20.4	23.1	21.8	17.0	11.8	1.2	-5.8
Tmin	-21.0	-16.5	-12.0	-3.1	2.9	7.1	9.2	7.8	3.2	-2.4	-10.0	-16.7
Precip	21.5	18.0	19.1	23.6	48.1	81.0	72.3	68.3	40.9	17.6	13.9	18.6
							Lethbridge					
Tmax	-4.5	0.3	4.1	11.4	17.6	21.7	25.6	24.5	19.3	13.9	5.0	-0.1
Tmin	-16.6	-11.7	-8.5	-1.7	3.9	8.2	10.4	9.4	5.0	0.2	-7.0	-11.9
Precip	23.4	18.6	23.9	41.3	48.5	78.1	47.4	38.3	36.5	17.8	22.0	21.9

Source: Atmospheric Environment Service, Canadian Climatic Normals 1951-1980: Temperature and Precipitation, Environment Canada.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46
30
48
64
41
51
Lethbridge
107
66
36
30
0
100
50
150
Kilometres

Figure 2.1 Mean Annual Precipitation (cm) in Alberta and Boundaries of East Central Alberta

Source: McGill, W.B., 1982, Soil Fertility and Land Productivity in Alberta, ECA 82-17/IB16, Environmental Council of Alberta, Edmonton, 123 pp.

Alberta is divided into agroclimatic zones based on the suitability of the climate for field production of spring wheat. Figure 2.2 shows these zones in Alberta and also includes the definition of these zones. Three agroclimatic zones encompass almost all of the cultivated land in east central Alberta -- zones 1, 2H, and 2A. Generally zone 2A has a semi-arid climate, zone 1 a subhumid climate, and zone 2H a subhumid to humid climate. Coronation and Lethbridge lie in agroclimatic zone 2A. Edmonton is contained in agroclimatic zone 1 while Lacombe is within agroclimatic zone 2H but near the boundary with agroclimatic zone 1.

2.4 Land and Soils

All the study region was glaciated during the last ice age. Most of the area is covered by glacial till which is composed of finely ground unstratified particles. The glaciers plastered the till onto the surface leaving behind large areas called ground moraines. In these areas the surface landform is undulating to rolling. The soils which developed on the till are generally medium to fine textured. Several large lakes were formed when the glaciers were melting. Where these lakes were located, today lies areas with a generally level topography and fine textured soils (much of the land immediately north and

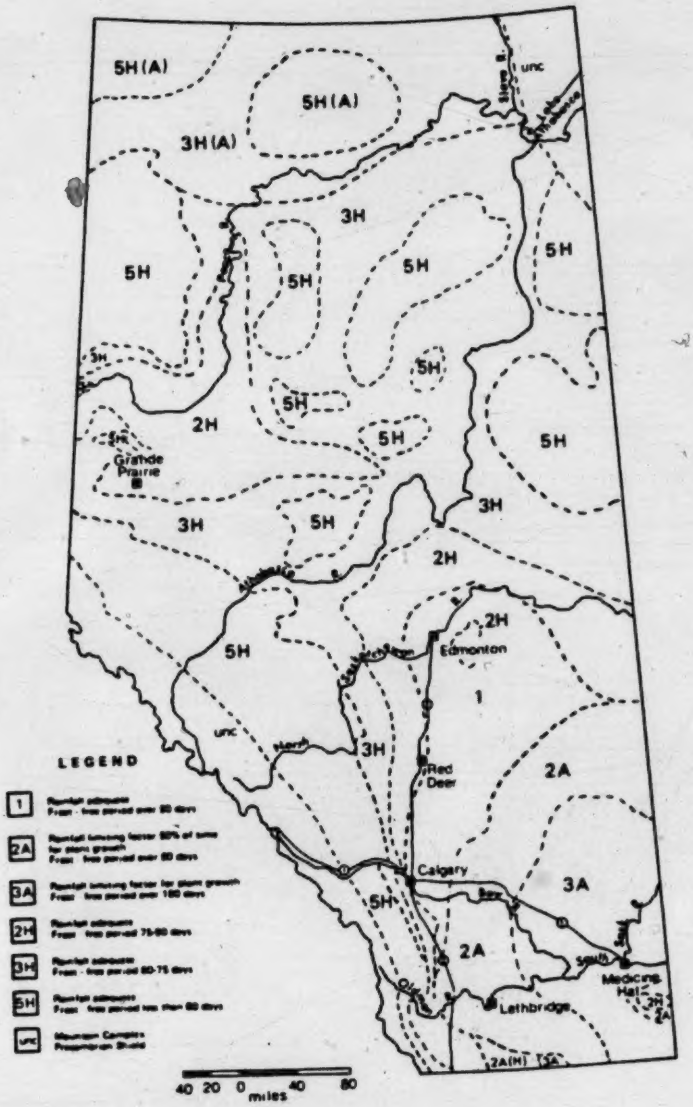

5H(A)
5H(A)
3H(A)
unc
Slave R.
3H
5H
5H
5H
5H
5H
5H
5H
5H
5H
2H
Grande Prairie
3H
5H
3H
2H
2H
Edmonton
5H
1
unc
3H
Red Deer
2A
Calgary
3A
5H
Bow
2A
South
Medicine Hat
Lethbridge
2A(H)
3A
LEGEND
1
2A
3A
2H
3H
5H
unc
40 20 0 40 80
miles

Figure 2.2 Agroclimatic Zones in Alberta

Source: Thompson, P.S., 1981, The Agricultural Land Base in Alberta, ECA 81-17/IB3, Environmental Council of Alberta, Edmonton, 111 pp.

south of Edmonton is an ancient lakebed). Therefore, the majority of presently farmed soils in east central Alberta are medium to fine textured with a level to rolling topography.

Water flowing from the glaciers sorted the materials it carried by size. Deposits from glacial outwash and from ancient watercourses produced the present day areas of coarse textured soils. An extensive belt of coarse textured soils exists in the eastern portion of the study region. This belt starts north of Wainwright and proceeds south and southeast into Saskatchewan. Within east central Alberta are a number of recessional moraines. Recessional moraines are hilly deposits of variable textures. An example of a recessional moraine is the Cooking Lake moraine where Elk Island National Park is situated.

According to the Canadian system of soil classification (Canada Soil Survey Committee 1978), most of the cultivated land in east central Alberta is composed of three orders -- Chernozemic, Luvisolic, and Solonetzic. The Chernozemic soils are divided into three great groups -- Dark Brown (developed on grasslands in a semi-arid climate), Black (developed on grasslands in a subhumid climate) and Dark Gray (developed under a forest-grassland transition in a subhumid to humid climate).

Chernozems are the best soils for either dryland or irrigated agriculture. These soils normally have good drainage, good soil structure and tilth, are inherently fertile, and relatively salt free.

Luvisolic soils developed under forest cover. These soils tend to have a low proportion of organic matter in the topsoil making them subject to crusting when their surfaces are impacted with water droplets. Also these soils contain an illuvial B horizon which can be nearly impermeable to roots or water, especially if the soil developed on fine textured parent material. Luvisols are not as naturally fertile as Chernozems and require more careful management.

Solonetzic soils are usually found in association with Chernozemic soils. These soils often occur as patches (less than 0.5 ha) within Chernozemic soils. Solonetzic soils developed on parent materials high in sodium salts. Deflocculated clay particles were deposited in the B horizon which forms a hardpan which can be almost impermeable to roots or water. Typically the surface of Solonetzic soils is pock marked with shallow pits which are 130 to 250 mm deep. Solonetzic soils are also subject to crusting when impacted with water drops. Because of the restricted root zone, crops on these soils are among the first to suffer in a drought. Crops on these soils also suffer during exceptionally wet periods because of the poor surface and internal drainage. Solonetzic soils require careful management if they are to be productive. (As used in this study, Solonetzic soils refer to soils with predominant Solonetzic properties whether they belong to the Solonetzic order or to the Chernozemic or Luvisolic orders.)

The irrigability of Solonetzic soils is a contentious issue. Karkanis (1982) believed Solonetzic soils are not favourable for irrigation development. Cairns and Bowser (1977) claimed Solonetzic soils often become saline if irrigated. Palmer (1982) stated some Solonetzic soils improve if irrigated because there is extra leaching of salts below the root zone. However, Palmer notes that Solonetzic soils with the groundwater table within one metre of the surface or with very restricted internal drainage can easily become waterlogged and/or saline if irrigated. Unfortunately, Palmer reported that predicting which Solonetzic soils are irrigable is difficult. In any event, Solonetzic soils require careful management if they are irrigated. Irrigation water in excess of crop needs can easily bring about waterlogging and/or salinization (Alberta Agriculture 1981a). Light, frequent applications are recommended.

The Canadian Prairies have been divided into a series of soil zones. Figure 2.3 shows the soil zones in Alberta. The soil zones describe both the climate and characteristic soils found in each zone. The Brown soil zone lies in a semi-arid to subarid climate and the characteristic soil is Brown Chernozems. Dark Brown Chernozems are the characteristic soils of the Dark Brown

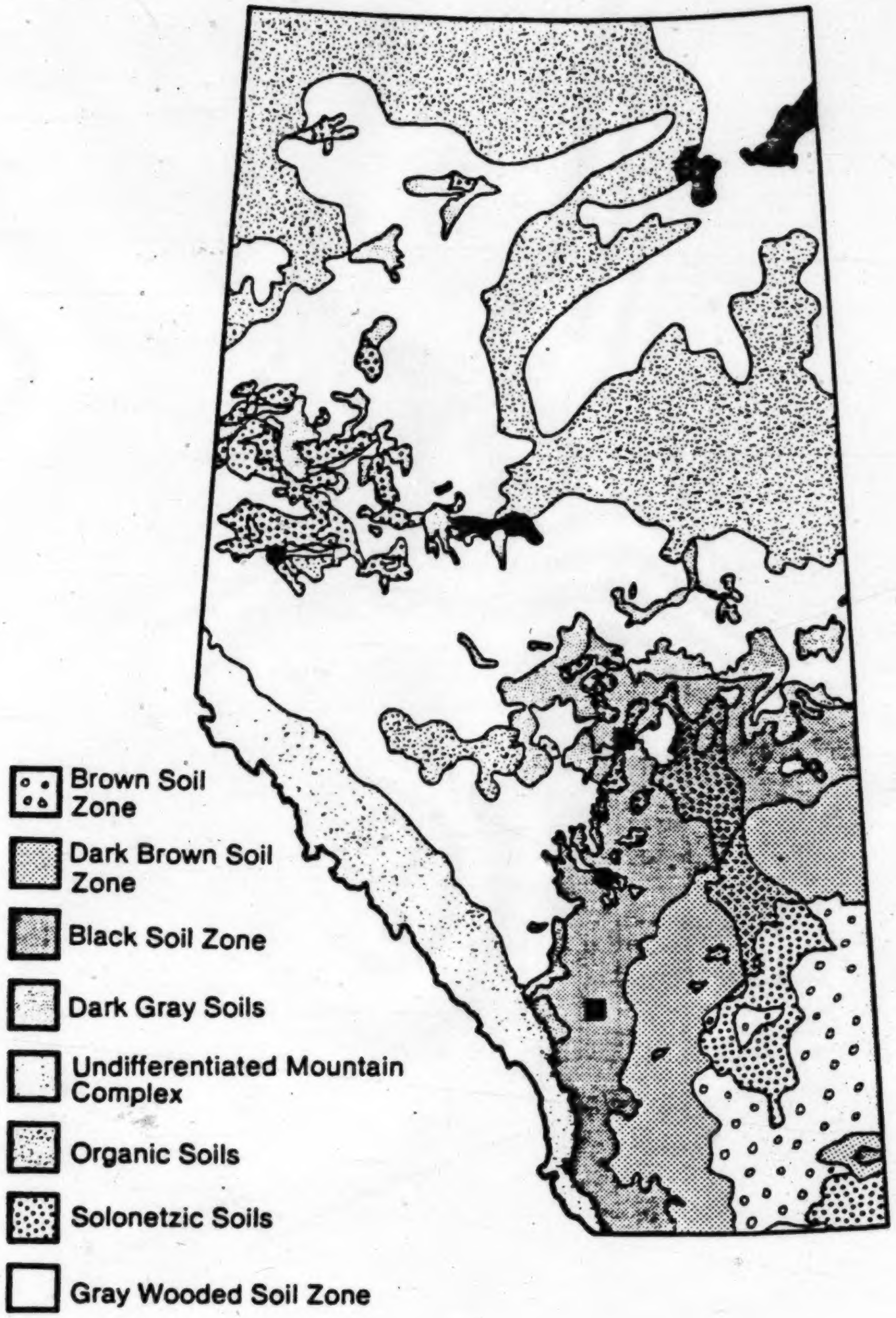

Brown Soil Zone
Dark Brown Soil Zone
Black Soil Zone
Dark Gray Soils
Undifferentiated Mountain Complex
Organic Soils
Solonetzic Soils
Gray Wooded Soil Zone

Figure 2.3 Soil Zones in Alberta

Source: McGill, W.B., 1982, Soil Fertility and Land Productivity in Alberta, ECA 82-17/IB16, Environmental Council of Alberta, Edmonton, 123 pp.

zone which has a semi-arid climate. The Black soil zone has a subhumid climate and characteristically contains Black Chernozems. One typically finds Dark Gray Chernozems and Dark Gray Luvisols in the Dark Gray zone which has a subhumid to humid climate with considerable risk of frosts during the growing season.

The properties which define land well suited to sprinkler irrigation are: free of rocks and stones, good surface and subsurface drainage, low salinity, good soil structure, not subject to frequent flooding, simple slopes less than 9%, complex slopes less than 5%, no restriction to penetration of roots or moisture, and a permanent water table below the root zone (Karkanis 1982). These are same properties which define good soils for dryland farming (Brocke 1977).

Most of the land which is farmed in Alberta has been rated with regard to its capability for dryland agriculture under the Canadian Land Inventory (CLI) program. In general, land which is rated as well suited for dryland crops would also be suited for sprinkler irrigation (providing an inexpensive source of irrigation water is available). However the CLI system is partially based on estimates of moisture conditions. Land where the climate is judged to have insufficient moisture (agroclimatic zones 2A and 3A) for dependable crop production is downgraded. Under irrigation, the natural moisture deficit would have no effect on crop production. In addition, coarse textured soils (loamy sands and sandy loams) are further downgraded because of their low moisture holding capacity. Again, when irrigated, soil texture, per se, does not have any effect on expected yields. Land with imperfect drainage may be adequately drained for dryland conditions but inadequately drained under irrigation. Barteski (1983) reported that land, which under dryland conditions has excess moisture after heavy rains, will be a perpetual problem under irrigation unless artificially drained. Soils with satisfactory dryland drainage may become waterlogged when heavy rains follow an irrigation or when irrigation water is applied in excess of crop water needs. These soils would be rated higher for dryland agricultural capability (CLI system) than for irrigated agricultural capability. CLI classification is done on 1:250 000 scale maps which are unsuitable for determining the irrigability of individual fields. However, providing corrections are made for CLI downgrading for dryland moisture deficits and for internal drainage, the CLI capability rating for agriculture can be used to make exploratory assessments of land irrigability. The CLI classification can be supplemented with soil profile information from Alberta Soil Survey reports which, in east central Alberta, are available on a 1:125 000 scale. Actual assessments of the irrigability of land should use information which is shown on 1:10 000 scale maps and preferably 1:5 000 scale maps (Karkanis 1982).

A cursory review of CLI classification and soil survey reports shows that east central Alberta contains much land suitable for sprinkler irrigation. The most common land limitations to irrigation development on presently cultivated land are imperfect to poor natural drainage, Solonetzic soils, and the presence of sloughs and low spots within the fields. Imperfect to poor drainage is a common problem on level land with fine textured soils. These soils have inherently low infiltration rates so water tends to collect in any low spot where it may remain for an undesirably long time. Sloughs and low spots restrict the mechanical movement of the irrigation equipment and thus limits the area which can be irrigated as one unit. This is especially important for centre pivots which are best suited to irrigating land where the lateral can revolve without impediment. A significant portion of land in east central Alberta has a topography which either is too sloping or too rough for sprinkler irrigation. This latter land is rarely cultivated at present. Of the potentially irrigable land in east central Alberta, the most important limitation to irrigation development is the absence of a nearby suitable water supply.

2.5 Water Resources

Either surface or subsurface water can be used for irrigation. The flow rates required for sprinkler irrigation systems varies from about 10 L/s for a small side roll system (<400 m of lateral length), to 45 L/s for a hard hose traveler, to 125 L/s for a high capacity centre pivot irrigating 53 ha in one revolution. General well yield maps indicated the prevalent formations in east central Alberta have safe (i.e. continuous) yields of 0.1 to 8 L/s (ECA 1978). Well yields and water quality both decrease with increasing distance from the foothills. Therefore, in the south west corner of the study region a small irrigation system may be able to use groundwater directly. Another possibility for utilizing subsurface water sources is to withdraw groundwater continuously at a low rate and store that water in a surface reservoir. Irrigation water could be withdrawn at high rates from the reservoir for short periods. Generally, however, irrigation in east central Alberta would have to depend on surface water sources. Subsurface water sources are relatively expensive because of the cost of well drilling and the large lifts required to bring the water to the surface. Therefore, where the choice exists between a surface and subsurface water supply, the surface water supply will be preferred.

Four rivers flow through east central Alberta which have their headwaters in the Rocky Mountains -- Athabasca, Pembina (which joins the Athabasca), North Saskatchewan, and Red Deer. There are a number of smaller streams of sufficient size that pioneers and original surveyors named them rivers -- Battle, Vermilion, Beaver, Amisk, Blindman, Redwater, Tawatinaw, Paddle, Medicine, and Sturgeon. Of these rivers, however, only the Blindman, Red Deer, and Battle flow in the drier southeastern and south central portions of the study region.

In addition there are many smaller streams of varying size and permanency. On the Prairies, flow in the smaller streams occurs primarily in the early spring during snowmelt. Invariably, these small streams would have to be impounded if they were to be used for irrigation.

Much of the agricultural land in east central Alberta can benefit from artificial drainage and/or consolidation of small sloughs (Rapp et al. 1983). Because of the problem of finding a suitable outlet for this drainage water, often it is best collected in one large dugout or slough. Supplemental irrigation is one way to dispose of the drainage water.

Within east central Alberta are hundreds of freshwater lakes and thousands of sloughs of varying permanency containing a wide range of quantities and qualities of water.

Consequently, east central Alberta contains an abundance of surface water resources. However, in no way does this mean all potentially irrigable land has a adjacent dependable supply of water.

Unfortunately, some of the same conditions which increase irrigation needs can also decrease the water supply available from small watersheds. Little snowmelt and/or dry weather in early spring reduce stored soil moisture and spring runoff. If ample precipitation does not fall during the growing season, irrigation demand is increased while the surface reservoir may contain insufficient water to allow complete irrigation for the entire season. A dry preceding year may leave an empty reservoir in the fall as well as a dry soil in the watershed. More snowmelt and early spring precipitation can infiltrate the dry soil and thereby decrease the runoff which is needed to replenish the reservoir. However, if there is rapid snowmelt while the soil surface is still frozen then there can be dry soil but abundant spring runoff. Where the water supply is derived from a small watershed, in most years there should be considerable excess supply so that there will be sufficient irrigation water when runoff is low and when several drier than normal years occur in sequence.

The province of Alberta through Alberta Environment controls allocation of all surface and subsurface water within Alberta. A license is required to use surface or

7

subsurface water except for domestic use and stock watering. The intention of allocation is to prevent any water source from becoming overdrawn. In decreasing priority for water allocation, the various uses are ranked as follows: 1) domestic, 2) municipal, 3) irrigation, 4) industrial, and 5) other. For supplemental sprinkler irrigation, Alberta Environment normally limits irrigators to 200 mm to 300 mm gross seasonal application over the entire licensed area (although this restriction is not strictly enforced).

2.6 Present Irrigation Development

Practically all irrigated land in Alberta lies south of east central Alberta. However there are a number of small irrigation projects in east central Alberta which have been developed by individual farmers.

The Water Rights Branch of Alberta Environment made available records of holders of licenses to use water for irrigation in the study region. These licenses date back to 1907. Of the 370 licenses, 55 were obviously for nonagricultural purposes (golf courses and parks). Excluding those licenses which were not for agricultural purposes revealed that 85 or nearly 27% were granted in the ten year period from 1973 to 1983. This indicates there is considerable recent interest in irrigation in east central

Alberta. Most of the licenses for sprinkler irrigation have been granted in the last 20 years.

Most of the irrigation licenses are for backflood (also called springflood) projects. With backflood irrigation spring runoff is impounded and spread onto adjacent level land. Little attempt is made to control water application. When the soil in the root zone has been thoroughly wetted any remaining excess water is drained away. Hence, one irrigation is made per year. Usually hayland is irrigated in this manner. Because of the low cost of backflood projects, even a marginal improvement in yields from the one irrigation makes the project profitable. Few backflood irrigation projects involve more than 20 ha.

The majority of license holders were south of township 50 and only eight were north of township 60. The license holders were distributed fairly evenly between the Fifth and Fourth Meridians.

Many license holders have discontinued irrigation or never proceeded with their irrigation plans. Also there are some illegal (unlicensed) irrigation projects. Therefore it is difficult to determine the exact amount of sprinkler irrigation in east central Alberta. Most of the sprinkler irrigated area is for grass sod (1350 ha principally near Red Deer and Edmonton) and potatoes (210 ha near Edmonton).

From the last 20 years of filed plans, 25 license holders who intended to use sprinkler irrigation were identified. Three of these licenses were for irrigating potatoes. These were not included in the study because the aim of the study was to investigate irrigation of more common field crops. Of the remaining 22 license holders, 12 were contacted (the rest had either moved or had unlisted phone numbers). Of the 12, only six had actually irrigated in the past and only one during the year contacted (1983). Five of the licensed sites were visited. Table 2.3 lists the irrigation method, irrigated crops, and water source for the actual irrigators contacted. In all cases, those with licenses owned land adjacent to a lake or river. All the irrigated soils were coarse to medium textured. The sites near the rivers had soils which developed on more coarse textured alluvial deposits.

The farmers using the hand-move systems were contemplating switching to irrigation methods requiring less labour input such as a traveling gun or a side roll. One of the hand-move irrigators applied about 65 mm on the hay during June if required. He found it too much work to perform more than one irrigation per season. The second growth was grazed in the fall. He estimated that yield was improved about 50% with the one irrigation in the spring. The other hand-move irrigator applied one 75 mm application during each hay growth if required. The primary advantages

Table 2.3 Systems, Crops, and Water Sources of Contacted Irrigating Farmers in East Central Alberta

System type	Crops	Irrigated Area (ha)	Water Source
1) four stationary centre pivots	wheat	170	Red Deer R.
2) big gun	hay & grain	40	lake
3) side roll	hay	36	lake
4) side roll	grass pasture	30	Red Deer R.
5) hand-move	hay	18	Vermilion R.
6) hand-move	hay	53	lake

this farmer stated for irrigation was assurance of two good cuts and better quality control (particularly delaying early blooming of alfalfa under dry conditions). He expected a 30 to 50% better yield with irrigation. The hay was managed just like dryland hay and was fertilized with manure.

The big gun is primarily used to spread liquid hog manure but the farmer has also irrigated both hay and grain during exceptionally dry periods. The hay responded better to the irrigation than grain. Because of the amount of work required to irrigate, the farmer was thinking of investing in a centre pivot.

The farmer irrigating tame hay with a side roll made a 100 mm application during the first and second growths if required. However this farmer had stopped irrigating several years ago because irrigated hay did not work with his crop rotation (he did not believe it was worthwhile to irrigate grain) and he had problems with his water source (intake clogging and conflict because the lake is used for recreation). The farmer irrigating pasture estimated that irrigation approximately doubled the carrying capacity of the pasture.

The farmer using centre pivots was completely hailed out in 1983. Before the hail the farmer was expecting the wheat crop to yield 4000 kg/ha. The farmer was interested in growing hay provided a good, consistent market for hay could be found.

The farmers with actual irrigation experience started irrigation whenever the soil was judged to be too dry. Several dug into the subsoil to estimate total profile moisture. Except for the farmer using centre pivots, all irrigators judged irrigation to be profitable, although not overwhelmingly so. The centre pivot project ended up costing much more than originally thought. Therefore, the farmer was not certain if the investment would ever be paid back.

The farmers who held licenses but had not yet invested in irrigation, invariably owned land beside a river or lake. They were all interested in irrigating tame hay only. The stated primary reason for considering irrigation was primarily to increase production and income without having to buy more land.

Hamlin (1983e) cites a survey of 300 irrigating farmers in Saskatchewan. Of these, 43% irrigated tame hay, 21% wheat, 15% barley, and 21% other crops. Of the respondents, 98% felt irrigation had either helped stabilize net farm income or increased net farm income. When asked if the benefits of irrigation exceed the costs, 60% responded significantly so, 35% replied marginally, and 4% felt the benefits approximately balanced the costs. The reasons chosen for irrigation (followed by the percentage of respondents choosing) were: a suitable water source was present (72%), desire to raise net farm income (62%), experienced droughts in the past (44%), desire to continuous crop (43%), additional farmland was unavailable (26%), government grants were available (26%), desire to stabilize forage supply (16%), and family wanted to start farming (15%).

The importance of having a good water source on deciding to irrigate is logical. The other reasons are similar to those found in east central Alberta -- increase yields to raise net income, an alternative to farming more land, or to reduce the effects of extended periods of dry weather. Many of the Saskatchewan irrigators are located in regions which have larger moisture deficits than east central Alberta. Therefore, these irrigators expectedly found that the benefits of irrigation farther outweighed costs than the irrigators contacted in east central Alberta.

3.0 Literature Review and Model Development

3.1 Computer-Aided Studies of Irrigation Systems

Studying the economics of irrigation involves consideration of crops, soils, weather, hydrology, markets, and water management. Together, these elements form a complex system. Consequently, system analysis is frequently used to study irrigated crop production. Essentially, system analysis refers to the study of an entire system rather than of one part of the system in isolation. Invariably, system analysis uses either conceptual models or mathematical models to represent the features of the system which the analyst believes are most relevant. The primary goal of system analysis is to manipulate system design and/or management to obtain the most benefit at least cost. The actual problem-solving techniques used by system analysis are often referred to as operations research.

One powerful system analysis tool is Monte Carlo simulation. With Monte Carlo simulation, system inputs are produced randomly from known distributions. These random inputs are called stochastic variables. System behavior is studied for each set of input variables. Analysis of historical behavior of the system is akin to Monte Carlo simulation since only a sample of possible inputs are involved. In irrigation studies, precipitation and atmospheric conditions are usually stochastic inputs. There is no standard formulation for Monte Carlo simulation models.

Dynamic programming is another technique system analysts use to solve problems which involves optimization of multistage decision processes. Stochastic dynamic programming includes the use of stochastic variables. Irrigation scheduling is a problem well suited to stochastic dynamic programming as irrigation entails ongoing decisions of when and how much water to apply considering the changing states of the crop, soil moisture, and expected future weather. Stochastic dynamic programming is particularly useful for finding optimal solutions to problems, such as irrigation, where some resources (e.g. labour and water) may be scarce.

Linear programming is another tool which has applications in water resource planning. Linear programming is suited to optimal allocation of scarce resources among competing uses. Linear programming has been used to allocate limited water among farmers within a irrigation district or determining what crops to plant if water supply is expected to be limited.

3.1.1 Computer-Aided Estimation of Irrigation Requirement

Numerous studies have used computer simulations of weather and soil moisture to predict the specific probabilities of irrigation requirements. Baier and Robertson (1967b, 1970) and Baier and Russelo (1968) analyzed the probable distribution of irrigation requirements and drainage needs for 42 locations across Canada. These probabilities are calculated on a weekly basis for several moisture storage capacities and several crop use rates. Ayers (1965) and Verma and Whitely (1981) used a similar approach to determine the supplemental irrigation needs in southern Ontario. Lake and Broughton (1969) used this method for southwestern Quebec and verified their model with actual field measurements of soil moisture. These studies showed that seasonal irrigation requirements are approximately normally distributed. Scott (1975) calculated probabilities of irrigation and drainage needs at Lethbridge as well as the probabilities of needing to start irrigation on specific dates.

All the above studies are useful for the design of an irrigation system. For actual irrigation scheduling, the probabilities of irrigation need from these studies are of less value. This is because they do not take into account the actual soil moisture. For example, if the soil is unusually dry, there will be more probability of needing irrigation than if there was average soil moisture. As a result, the probabilities of irrigation need can not be used directly to determine the quantity of irrigation to apply in one year.

3.1.2 Monte Carlo Simulations Considering Yield

Gray et al. (1966) considered the probability of occurrence of peak consumptive use at Saskatoon. They concluded a sprinkler system must be designed to meet some probability of peak use and this probability must be determined from an economic analysis. If a sprinkler system can not always supply crop moisture requirements, the capital cost of the system is reduced but the farmer must occasionally expect reduced yields during weather with no rain and above normal PET. However for forage crops, where two annual harvests are made, the occasional reduced yield for one harvest may be an acceptable trade-off for lowering capital costs.

English (1981) concluded the uncertainty in yield is very important in choosing optimal irrigation strategies or choosing what crops to plant. When optimal irrigation strategies are based strictly on maximizing average returns, there can be the chance of having years with unacceptably low returns. Many farmers are averse to risk and will prefer an irrigation strategy which tries to both maximize expected profit and minimize the uncertainty of that profit. The farmer is the only one who can choose which crops to irrigate and the best irrigation strategy.

von Bernuth et al. (1983) used a computer simulation to estimate optimal irrigation system capacities for irrigated corn in Nebraska. They included estimates of the probabilities of yield reduction for each system capacity.

Stegman and Bauer (1970) used a computer simulation model to investigate the best irrigation strategy for a centre pivot used to irrigate a field of wheat and another of corn in North Dakota. Irrigation was started when 65% of plant available soil moisture (AM) was depleted. They found the number of moves required per year was approximately normally distributed with a mean of 6.0 and a standard deviation of 1.5. Based on the number of days of high moisture stress, the system provided adequate performance in all years.

Hill and Keller (1980) developed a computer simulation model to explore the influence of application uniformity on the economics of crop production. They developed crop production functions from actual field yield trials. Using the model, they studied the impact of sprinkler system design on application uniformity and on net monetary returns. Although they restricted their study to sugar cane, they felt the approach held promise for optimizing sprinkler irrigation design for other crops.

In humid regions, Lembke and Jones (1972) noted that irrigation is a more difficult problem than in more arid regions. Irrigating too soon may leach valuable nutrients below the root zone or produce drainage problems in soil without good natural drainage. They developed a computer simulation model to determine the optimal soil moisture depletion at which to start irrigation of corn in Illinois. Among their findings was that scheduling irrigation based simply on quantity of antecedent rainfall may be as useful as the more conventional method of scheduling irrigation based on soil moisture depletion.

Apland et al. (1980) developed a mathematical model to investigate the economic feasibility of supplemental irrigation of corn in the United States corn belt. They concluded that the increased production due to irrigation approximately balanced the irrigation costs. However, irrigation did reduce the variability in crop yields. Therefore, supplemental irrigation was a worthwhile investment for risk averse farmers. Only the farmer can place the exact value on irrigation.

Dyalla et al. (1980) constructed a computer simulation model to study sprinkler irrigation practices for corn grown in southern Minnesota. They included the effect of uneven application over the field. Reducing crop moisture stress and minimizing nutrient leaching were the joint objectives of this study. They concluded that frequent, light irrigations were optimal.

Mapp et al. (1975) designed a computer simulation model to investigate ways to increase the efficiency of water use for irrigated corn, wheat, and sorghum in Oklahoma. They concluded the model performed well to predict crop moisture requirements and the effects of unavailability of water at certain periods during the growing season.

Some irrigated land requires subsurface drainage. Hart et al. (1980) constructed a computer model to optimize sprinkler irrigation practices in order to minimize drainage costs. They included the impact of application uniformity on soil moisture status.

Stewart et al. (1974) assembled an elaborate computer simulation to predict optimal irrigation strategies for any given level of irrigation water supply. They used the model to simulate irrigated corn in central California. They also allowed for variation in uniformity of application depth.

Swaney et al. (1983) used a computer simulation to aid an irrigator in making irrigation decisions during the season. The model produced estimates of the returns from irrigating individual fields on the current day or from delaying irrigation. The model also calculated the expected variation in returns. They applied the model to irrigated soybeans in Florida.

3.1.3 Irrigation System Analysis Using Dynamic Programming

Dynamic programming has been widely applied to estimate the optimal allocation of water over the season given a limited supply of water. Table 3.1 lists many of the studies found in the literature which employ dynamic programming. All aim to maximize net returns from irrigation except that of Howell et al. (1975) which strives to allocate water to maximize yield.

Like Monte Carlo simulation, there is no standard formulation of a dynamic programming model. Each dynamic programming study listed in Table 3.1 simulated soil moisture, ET, precipitation, PET, the irrigation system, and crop yield. Generally the growing season is split into several simulation periods. Weather, yield and irrigation decisions are calculated for each period.

Dynamic programming suffers from the curse of dimensionality (Larson and Casti 1978). This means that as more factors are introduced into the model the number of calculations increases linearly. This is most pronounced when stochastic factors are included whose distribution must be represented by a number of discrete values. For this reason, dynamic programming models tend to be fairly simple or they would require infeasible amounts of computer time and/or high speed memory to implement.

Table 3.1 Irrigation Studies Employing Dynamic Programming

Location	Crop(s)	Authors
Australia	methodology only	Flinn and Musgrave (1967)
United States	methodology only	Hall and Butcher (1968)
Australia	corn	Dudley et al. (1971)
Illinois	corn and soybeans	Windsor and Chow (1971)
Missouri	corn	Burt and Stauber (1971)
Texas	sorghum	Howell et al. (1975)
Nebraska	corn	Martin et al. (1983)
Colorado	corn	Bras and Cordova (1981)
Colorado	corn	Rhenals and Bras (1981)

If stochastic variables are overly simplified, the solution resulting from dynamic programming can be suboptimal (Morin 1973). When solving for maximum net returns, the dynamic solution gives no indication of the variability of net returns and yields. Yet, this variation may be the major concern of the irrigator.

3.1.4 Model Outline

Essentially, the goal of the simulation model was to simulate many years of field-scale irrigation trials. Two hypothetical land areas were modeled -- a dryland field and an adjacent irrigated field. These areas contained the same soil and were subjected to identical weather. Yields were compared for each year with and without irrigation. The net returns from irrigation were defined as the dollar value of the difference in yields less the costs which can be attributed to irrigation. These returns were also analyzed each year.

The simulation was done on a daily basis so that the model would be responsive to small changes in irrigation system management. Simulating on a daily basis makes the model of weather-soil-crop too large for inexpensive analysis with a dynamic programming algorithm. Therefore the system analysis approach used was the Monte Carlo method. A Monte Carlo simulation was particularly well suited to this study because it preserves the yearly variation in yields and returns. With Monte Carlo simulation, the optimal irrigation practices are arrived at by educated trial and error. The pattern of irrigation water needs, yields, etc. from many simulated years are examined for each set of input parameters such as scheduling criteria, irrigation system type, irrigated area, etc. The modeler decides what new set of parameters to try.

Essentially the model is divided into 13 submodels most of which in turn are divided into smaller subprograms. Appendix A contains a flow chart of the entire computer model. The program was implemented in PL1. PL1 (Programming Language 1) is a general purpose high level computer language. Appendix B contains a listing of the entire program. PL1 proved to be a good choice for a modeling language as it was relatively easy to develop and debug the program. Also, PL1 appeared to be less expensive to compile and run than other high level languages available on the University of Alberta computer system.

The simulation season ran from April 9 to October 15. These limiting dates were chosen because they encompass the majority of the year when the soil surface is unfrozen. The model assumes all daily precipitation infiltrates the soil on the day it falls. Between these dates, most precipitation falls as rain or, if snow, melts soon after falling. The assumptions of melting snow and unfrozen soil may not be valid in all years, particularly in April. However it was important to start the simulation as early as possible in the spring to include the effect of early spring weather on soil moisture and crop growth.

Once irrigation has begun, the soil moisture varies across the field with the intermittent move irrigation systems (side roll and hard hose traveler). To account for this, soil moisture and crop growth were modeled independently for three positions on the field: the first (starting) set, the middle set, and the final (stopping) set. Irrigated yields and moisture use were the simple average of all these modeled positions. Normally a centre pivot makes a revolution in less than two days. Therefore, the variation in soil moisture across the field due to the delay in system movement is not important. For a towable pivot, however, there exists a difference in soil moisture between each irrigated circle. Each area irrigated by a towable pivot was modeled individually. It was assumed all land irrigated by the towable pivot was in the same crop. Therefore, again, irrigated yields and moisture use were the average of all the modeled positions.

3.2 Weather Model

Because of the relative shortness of complete weather records and the occurrence of days with missing data, the weather was generated artificially rather than using the historical data. The basic simulation method used was similar to that of Jones et al. (1972), Scott (1975) and Howell et al. (1975).

Weather was simulated on a daily basis using weather probabilities gathered for ten day periods. The assumption was made that there were no important trends in weather probabilities during each ten day period. All the weather probabilities changed in discrete steps rather than continuously as in the real world. However, any distortion this caused was obscured by the considerable daily variation in each modeled weather element. An implicit assumption of the weather generation technique was that the best estimate of future weather was historical weather. Therefore, any significant climatic changes will be missed by the weather generator.

The relationship among the weather variables was summarized as:

$$W = f(t,RV) \tag{3.1}$$

$$R = f(t,W,RV) \tag{3.2}$$

$$Tmax = f(t,W,RV) \tag{3.3}$$

$$Tmin = f(t,Tmax,W,RV) \tag{3.4}$$

$$PET = f(t,Tmax,W,RV) \tag{3.5}$$

where:

t is the particular weather generation ten day period,

W indicates if the day is wet or dry,

R is daily precipitation,

Tmax is daily maximum temperature (°C),

Tmin is daily minimum temperature (°C),

PET is modified Penman PET estimate (mm/d),

RV is a random variable drawn from the observed variation in each variable.

Random number generators were used to produce the random component in each weather variable. The uniformly distributed random number generator used the following equation:

$$S(i+1) = \mathrm{MOD}((\ 24298 * S(i) + 99991),\ 199017) \tag{3.6}$$

$$U = S(i+1)/199017 \tag{3.7}$$

where:

$S(i)$ is a seed number for invocation i ($0 < S(i) < 199017$),

U is a random number uniformly distributed between 0.0 and 1.0.

Weather variables following a normal distribution were generated by:

$$x = m + G * SD \tag{3.8}$$

where:

x is the weather variable,

m is the observed mean of the weather variable,

SD is the standard deviation of the weather variable,

G is a random deviate which is normally distributed with a mean of 0.0 and a variance of 1.0.

The normally distributed random deviate was generated from:

$$G = \mathrm{SQRT}(\ -2.0 * \ln U_1) * \mathrm{COS}(6.28 * U_2) \tag{3.9}$$

where:

U_1, U_2 are uniformly distributed random numbers generated from equation (3.6)

Identical weather patterns for the desired number of seasons could be produced by inputting the same initial seed number into the uniformly distributed random number generator. This allowed easy comparison between different irrigation system design parameters or management practices.

Weather records were obtained from the Atmospheric Environment Service of Environment Canada for Coronation Airport, Edmonton International Airport, Agriculture Canada Lacombe Research Station, and the Red Deer-Penhold Airport. Table 3.2 lists the geographical location, the type of weather records obtained, and the years of data collection for these stations. In addition to these records, 50 years of daily precipitation and temperature data for Lethbridge Airport (latitude 49.7° N, longitude 112.78° W, 903 m above sea level) were obtained courtesy of Alberta Agriculture (Engineering and Rural Services Division).

Table 3.2 Weather Stations and Records

	Cor.	Edm.	Lac.	R.D.-Pen.
Latitude (°N)	52.12	53.32	52.47	52.18
Longitude (°W)	111.45	113.58	113.75	113.90
Elevation (m)	789	713	847	905
Years of Record				
Daily Temp. & Precipitation	1944-1982	1959-1982	1907-1982	1938-1982
Hourly Bright Sunshine	1975-1982	1968-1982	1953-1982	---
Hourly Relative Humidity	1953-1982	1961-1982	---	1953-1982
Hourly Winds	1952-1982	1961-1982	---	1953-1982

3.2.1 Precipitation

The transition from one state (e.g. a dry day) to another (e.g. a wet day) often follows a simple (or first order) Markov chain (i.e. the chance of having one state equals the transitional probability from the previous state). Hopkins and Robillard (1964) found a simple Markov chain adequately describes the length of wet and dry days at Edmonton, Swift Current, and Winnipeg from April to September. They also found the transitional probabilities changed throughout the season. Feyerherm and Bark (1967) concluded the simple Markov chain described the lengths of wet and dry spells in Kansas, Missouri, Iowa, and Indiana.

Scott (1975) tested and found a simple Markov chain could be used to realistically simulate the occurrence of wet and dry days at Lethbridge. Scott used separate transitional probabilities for each two week period from April to October.

The 190 day simulation period from April 9 to October 15 was divided into 19 ten day spans. The transitional probability of a wet day following a dry day and of another wet day following a wet day were calculated from historical weather data for Edmonton, Coronation, Lacombe, and Lethbridge. A dry day was defined as a day with less than 0.25 mm of precipitation.

The relevant equations were:

$$W(i-1) = 0: \quad W(i) = 0 \text{ if } U >= P(W/D)$$
$$W(i) = 1 \text{ if } U < P(W/D) \tag{3.10}$$

$$W(i-1) = 1: \quad W(i) = 0 \text{ if } U >= P(W/W)$$
$$W(i) = 1 \text{ if } U < P(W/W) \tag{3.11}$$

where:

W(i-1) is the state of the day i-1
(0 = wet, 1 = dry),

W(i) is the state of day i,

P(W/D) is the transitional probability of wet day following a dry day during each ten day period, P(W/W) is the transitional probability of a wet day following a wet day during each ten day period.

Kendall (1966) reported that the cube root of precipitation for daily to monthly periods is approximately normally distributed for locations in Canada and elsewhere in the world. Johnston and Hendricks (1974) found the cube root of daily, weekly, and monthly rainfall was normally distributed at Regina. To test this hypothesis, 12 years of daily precipitation on wet days at Camrose during the periods of May 1 to 10, June 21 to 30, August 1 to 10 and September 11 to 20 were analyzed. Camrose lies near the centre of the study region. Using the method given in Loucks et al. (1981), the Kolmogorov-Smirnov test was used to determine whether precipitation followed a cube root normal distribution. All points lay within the 90% confidence limits except one point in September which was below the lower 90% confidence limit but within the 95% confidence limits.

The mean and standard deviation of the cube root of daily precipitation on wet days were calculated for each 10 day period for Coronation, Edmonton, Lacombe, and Lethbridge. To generate simulated daily precipitation the following equation was used:

$$R = (m + G * SD)^3 \tag{3.12}$$

where:

R is daily precipitation on wet days,

m is the mean of the cube root of precipitation,

G is a normal deviate from equation (3.9),

SD is the standard deviation of the cube root of precipitation.

3.2.2 Temperature

Both daily minimum and maximum temperatures were generated. Invariably the observed average Tmax was higher on dry days than on wet days and Tmin was lower on dry days than on wet days. This temperature behavior can be explained by the normally greater cloud cover on wet days. To retain this difference separate temperature statistics were gathered for wet and dry days during each ten day period.

The daily maximum temperature for each ten day period was assumed to be normally distributed and independent of the previous day's maximum temperature. The equation used was:

$$Tmax = m + G * SD \tag{3.13}$$

where:

m is the observed average Tmax for wet or dry days during each ten day period, G is a normal deviate from equation (3.9),

SD is the observed standard deviation of Tmax for wet or dry days during each ten day period.

A regression analysis was performed on Tmax and Tmin. Separate regression analyses were carried out for wet and dry days during each ten day period. Generally Tmin was virtually independent of Tmax, especially during June, July, and August. However, in the simulation, Tmin was generated as a function of Tmax. This was done to preserve what linkage existed between these variables as well to reduce the incidence of the generated minimum daily temperature exceeding the maximum temperature (if this did occur the temperature values were switched). The equation used was:

$$\text{Tmin} = a + b * \text{Tmax} + G * \text{SE} \qquad (3.14)$$

where:

a is the regression intercept of Tmin on Tmax,

b is the regression slope of Tmin on Tmax,

G is a normal deviate from equation (3.9),

SE is the standard error of estimate from regression of Tmin on Tmax.

Longley (1972) stated that the mean daily temperature, Tmean, for Alberta locations can be calculated as a simple average of Tmax and Tmin. Longley claimed this average is not significantly different from Tmean calculated by averaging hourly temperatures. Therefore, for the weather simulation, Tmean was estimated as:

$$\text{Tmean} = (\text{Tmax} + \text{Tmin})/2 \qquad (3.15)$$

3.2.3 Potential Evapotranspiration

Because it is difficult to separate plant transpiration and evaporation from the soil and plant surfaces, they are usually combined into one term -- evapotranspiration (ET). Potential evapotranspiration (PET) refers to ET when moisture is not limiting (i.e. the soil is kept consistently moist).

Despite the fact that PET is a widely used entity, it does not have a precise laboratory definition. PET is frequently estimated from indirect measurements. One procedure is to estimate PET by measuring evaporation of water from evaporation pans. Environment Canada maintains a network of standard U.S. Weather Bureau Class A pans in Alberta. These pans are 1.2 m in diameter, 0.25 m deep and elevated 0.15 m above the ground. Evaporation from a Class A pan generally exceeds ET from a well-watered crop. Pan evaporation is multiplied by a locally derived coefficient to estimate PET for a crop at a particular growth stage. Many Agriculture Canada Research Stations maintain evaporation tanks. These tanks are 1.2 m in diameter with a depth of 0.6 m and are placed in the soil. Again a set of coefficients are employed to convert tank evaporation to approximate crop PET.

Atmometers are instruments to measure atmospheric demand for water. They consist of a porous plate constantly supplied with water from the non-exposed back side of the plate. Measured water loss is termed latent evaporation. Two atmometers which have been widely used in western Canada are the black Bellani plate and the Gen atmometers. Latent evaporation can be converted to approximate PET by a set of coefficients.

A number of estimation techniques have been developed to estimate PET from meteorological variables. The Blaney-Criddle method incorporates the mean monthly temperature, monthly percentage of annual daylight hours, and an empirical crop and location dependent coefficient to estimate monthly PET. The Jensen-Haise method uses humidity, temperature, solar radiation combined with site elevation, and an empirical crop and location dependent constant to approximate PET for periods ranging from five days to one month. Both the above two procedures were specifically designed for use in the irrigated regions of the western United States.

The Thornthwaite method uses mean monthly air temperature and monthly daylength to form an estimate of monthly PET. The Thornthwaite method was designed to be a simple calculation for hydrological purposes.

Baier and Robertson (1965) used regression analyses to link daily latent evaporation from a black Bellani plate atmometer to meteorological and astronomical variables. They used five years of data gathered at six locations across Canada for the months for May through October. A family of eight regression equations were produced. All equations used daily maximum and minimum temperatures and calculated solar radiation at the top of the earth's atmosphere. Each equation differed by the inclusion or exclusion of measured solar radiation, vapour pressure deficit, and daily windrun. The simplest method using only daily maximum and minimum temperatures and solar radiation at the top of the earth's atmosphere accounted for only 46% of the observed variation in latent evaporation. The most complete equation, using all variables, explained the maximum amount (71%) of the variation. Using regression techniques, Baier (1971) found latent evaporation estimates (cm^3/d) can be converted to approximate crop PET (mm/d) by multiplying by 0.086.

Based on experiments in the Okanagan Valley, Wilcox (1963) recommended using the black Bellani plate atmometer over evaporation pans to estimate PET. Pelton (1964), however, analyzed data from Swift Current and decided more work was required before atmometers could be recommended over evaporation pans. Both authors observed that ET is more closely correlated with temperature and solar radiation than with wind or atmospheric water vapour pressure deficit.

Penman (1948, 1956) developed an approach for estimating PET by combining an energy balance with mass transfer equations. The Penman method has been found to produce satisfactory estimates of PET in a wide range of climates (Ward 1975).

van Bavel (1966) tried to eliminate the empirical constants inherent in the mass transfer portion of the Penman method. However, the van Bavel approach is still largely empirical (Szeicz et al. 1969, Jensen et al. 1971, Saxton et al. 1974, Slabbers 1977).

Hobbs and Krogman (1966, 1968) compared PET estimates from buried tanks, black Bellani plate atmometer, and the Blaney-Criddle, Thornthwaite, Jensen-Haise, and Penman methods with measured ET from well-watered alfalfa at Vauxhall. The Thornthwaite method underestimated PET by 50% but the other methods, with local calibration, gave serviceable estimates of monthly PET. Korven and Pelton (1967) found the Penman method gave the best agreement between estimated and measured daily PET from alfalfa at Swift Current compared with either the Blaney-Criddle or Thornthwaite method.

3.2.4 Penman Potential Evapotranspiration

A review of the literature revealed the Penman method of estimating PET, albeit with many modifications, has become a standard technique for computer-based estimation of PET where sufficient climatological data is available. When calibrated, the Penman method is suitable for time periods ranging from one hour to one month (Burman et al. 1980).

Essentially the Penman method combines the drying power of the air, as indicated by the atmospheric water vapour pressure deficit and the wind speed, with the energy received from solar radiation. The radiation is further divided into that which goes into sensible heat (i.e. raising the air temperature) and into latent heat (i.e. evaporation of water). Because the Penman method mixes mass transfer with an energy balance it is sometimes referred to as the combination equation.

The basic equation of the Penman method was:

$$PET = 10.0 * [(v/(v + g)) * (Rn + H) + (v/(v + g)) * 15.36 * W * (Ea - Ed)]/L \qquad (3.16)$$

where:

PET is the Penman PET estimate (mm/d),
10.0 is a proportionality constant (mm/cm),
v is the slope of vapour pressure-temperature curve (mb/K),
Rn is net radiation ($cal/cm^2/d$),

H is soil heat flux ($cal/cm^2/d$),

W is the dimensionless wind function,

Ea-Ed is the mean daily atmospheric water vapour pressure deficit (mb),

15.36 is a proportionality constant ($cal/(cm^2*d*mb)$),

L is the latent heat of vapourization (cal/cm^3).

Heat flux into or out of the soil is usually small relative to other terms and is often ignored (Ward 1975), especially for daily PET calculations (Burman et al. 1980, Staple 1974)

The following approximations (equations (3.17) to (3.20)) are from Burman et al. (1980).

$$v = 2.0*(0.00738*Tmean+0.8072)^7-0.00186 \quad (3.17)$$

$$g = 0.386 * P / L \quad (3.18)$$

where:

P is the average station barometric pressure (mb) and P = 1013 - 0.1055 * Elev where Elev is the station elevation above sea level (m).

$$L = 595 - 0.51 * Tmean \quad (3.19)$$

The saturation vapour pressure (Es) at any temperature T, (°C) was:

$$Es = 33.8639 * [(0.00738 * T + 0.8072)^8 - 0.000019 * ABS(1.8 * T + 48) + 0.001316] \quad (3.20)$$

The maximum saturation vapour pressure, Ea, was calculated at the mean daily air temperature. The actual vapour pressure, Ed, was calculated from mean daily relative humidity, RH:

$$Ed = RH * Es \quad (3.21)$$

The wind function, W, is empirical in nature. W is usually found from regression analysis and is of the form:

$$W = Aw + Bw * U_2 \quad (3.22)$$

where:

Aw, Bw are regression constants,

U_2 is daily wind travel at 2 m above the ground surface (km/d).

Table 3.3 gives the values of Aw and Bw from the literature based on calculating Ea from Tmean. Pelton and Korven (1967) felt the original Penman wind function constants (1.0 and 0.00621) underestimated the effect of the wind on PET at Swift Current. In this study, values of 1.0 for Aw and 0.01 for Bw were used since they appeared most representative and also give a larger value to W than the original Penman constants.

Table 3.3 Wind Function Constants for the Penman Equation

Aw	Bw	crop	Author(s)
1.0	0.00621	clipped grass	Penman(1948)
1.0	0.01	grass	Doorenbos and Pruitt (1977)
1.0	0.01	alfalfa	Jensen et al. (1971)
0.75	0.0115	alfalfa	Wright and Jensen (1972)

The following formula was used to estimate U(2) from the measured wind travel at z metres above the ground surface, U(z) (Burman et al. 1980):

$$U(2) = U(z) * (2.0/z)^{0.2} \tag{3.23}$$

Wind measurements at Edmonton, Red Deer-Penhold, and Coronation were all taken at 10.1 m. To estimate wind measurements at 2 m above the surface, the measured values were multiplied by 0.723.

Net radiation, Rn, was calculated from:

$$Rn = (1 - a) * Rs - Rb \tag{3.24}$$

where:

a is the crop albedo or reflectance,

Rs is the incoming solar radiation ($cal/cm^2/d$),

Rb is the outgoing long wave radiation ($cal/cm^2/d$).

Rs is normally calculated from a regression analysis as:

$$Rs = (As + Bs * n/N) * Ro \tag{3.25}$$

where:

As, Bs are regression constants,
n is the actual daily hours of bright sunshine,
N is daylength in hours,
Ro is solar radiation at the top of the earth's atmosphere ($cal/cm^2/d$).

Selirio et al. (1971) reviewed values of As and Bs found in the literature. Values of As range from 0.18 to 0.25 and Bs from 0.48 to 0.62. At Guelph, they empirically determined values for As and Bs of 0.23 and 0.57, respectively. Baier and Robertson (1965) used radiation measurements at Edmonton and Ottawa and calculated values of 0.251 and 0.616 for As and Bs, respectively. The values of As and Bs used in this study were 0.24 and 0.595 which were used by Staple (1974) for estimating net radiation at Swift Current.

Merva (1975) presented an extensive table of albedos of many surfaces. Burman et al. (1980) suggested using an albedo of 0.23 for irrigated crops. Gray et al. (1966) found the Penman method produced good estimates of PET at Saskatoon using an albedo value of 0.25. This latter value was used in this study.

Solar radiation at the top of the earth's atmosphere was estimated from (Kreith and Black 1980):

$$Ro = 888.8 * (1 + 0.033 * COS(360 * d/365) * (COS(Lat) * COS(DN) * COS(Ws) + 0.01745 * Ws * SIN(Lat) * SIN(DN)) \quad (3.26)$$

where:

Ro is the daily extraterrestial radiation ($cal/cm^2/d$),

d is the day of the year (Jan 1=1, Jan 2=2, etc.),

Lat is the latitude (°),

DN is solar declination (°),

Ws is solar angle at sunrise (°).

Solar declination was estimated from:

$$DN = 23.45 * SIN(0.9863 * (284 + d)) \quad (3.27)$$

Solar sunrise angle was found from:

$$Ws = COS^{-1}(-TAN(Lat) * TAN(DN)) \quad (3.28)$$

Total hours of daylight were calculated from:

$$N = 0.1333 * Ws \quad (3.29)$$

Outgoing long wave radiation, Rb, was estimated from Penman (1956):

$$Rb = (0.1 + 0.9 * n/N) * Rbo \quad (3.30)$$

where:

Rbo is outgoing net radiation ($cal/cm^2/d$) on a clear day.

Rbo was estimated from:

$$Rbo = (Ar + Br * SQRT(Ed)) * SB * Tk^4 \qquad (3.31)$$

where:

Ar, and Br are experimental constants,

SB is the Stefan-Boltzman constant ($1.14\ E\ {-7}\ cal/cm^2/K^4/d$),

Tk is mean daily air temperature (K).

Values of Ar and Br found in the literature are listed in Table 3.4.

Pelton and Korven (1969) compared PET estimates using Penman's radiation constants (0.56 and -0.09) with those using measured net radiation. They concluded there was little difference between PET estimates using either measured and estimated radiation. Based on this, Ar and Br of 0.56 and -0.09, respectively, were used to calculate outgoing long wave radiation.

Both Edmonton International Airport and Coronation Airport have fewer years of sunshine records than other meteorological data. To extend the number of years of PET estimates, Baier and Robertson's (1965) estimate of daily latent evaporation from an atmometer was calculated from daily maximum and minimum temperatures, solar radiation at

Table 3.4 Experimental Constants for Estimating Outgoing Long Wave Radiation

Ar	Br	Author(s)
0.56	-0.09	Penman (1956)
0.34	-0.044	Doorenbos and Pruitt (1977)
0.39	-0.05	Burman et al. (1980)
0.31	-0.044	Heerman et al. (1974)

the top of the earth's atmosphere, relative humidity, and wind run. On days when both latent evaporation and Penman PET estimates were known, a separate linear regression was performed of Penman PET on latent evaporation for wet and dry days during the entire 190 day period from April 9 to October 15. When only the latent evaporation estimate was known, an estimate of Penman PET was made using the regression constants. A separate regression analysis was then performed of PET on maximum daily temperature for wet and dry days for each ten day period. The coefficient of determination (r^2) for these regressions usually ranged from 0.45 to 0.65 with extreme values of 0.22 and 0.75. This showed there was a high correlation between maximum temperature and PET on either wet or dry days over these short time periods. The equation used to generate PET was:

$$PET = a + b * Tmax + G * SE \qquad (3.32)$$

where:

a, b are regression constants,

G is the normal deviate from equation (3.9),

SE is the standard error of estimate from regression of PET on Tmax on wet and dry days during each ten day period.

The climatic data for Red Deer-Penhold were merged with those of Lacombe to have a complete set of data to calculate PET. Precipitation and temperature data were used from Lacombe because the period of record was longer than at Red Deer-Penhold. Relative humidity and wind measurements were only available for Red Deer-Penhold while sunshine measurements were only available for Lacombe. Weather generated from the probabilities derived from this combined data set was assumed to apply to Lacombe.

Only temperature and precipitation data were available for Lethbridge. Lacombe and Lethbridge have similar patterns of monthly precipitation. Average ten day PET estimates were created for Lethbridge by assuming the PET for the two locations were in the same proportion as Class A pan evaporation. These latter PET estimates were altered by inspection so that PET formed a relatively smooth curve with time. Based on this procedure PET estimates at Lethbridge were about 110% of those at Lacombe in the early spring, 120-135% in mid summer and 150-200% in the fall.

PET for Lethbridge was generated by modifying the PET regression constants calculated for Lacombe. The slope of the regression equation of PET on Tmax at Lacombe was assumed to apply at Lethbridge. For simulation purposes, a correction was made to the PET estimates to account for the fact that Lethbridge has a higher number of dry days during the growing season than Lacombe. The PET estimates based on pan evaporation ratios were multiplied by the proportion of dry days at Lacombe during each ten day period over the similar proportion at Lethbridge. Without this correction, the ratio of PET at Lethbridge to that at Lacombe would be greater than the pan evaporation ratio because Lethbridge has more dry days (which usually have larger PET). A new intercept was derived as the difference between the modified PET at Lethbridge and the PET component derived from Tmax alone. The standard error of estimate for PET on Tmax at Lethbridge was assumed to be the same as that at Lacombe.

Penman PET as calculated by equation (3.16) is approximately valid for well-watered established alfalfa whose leaves form a complete cover over the soil. A crop coefficient is applied to convert this PET estimate to other crops. The crop coefficients are generally different for each distinct crop growth stage to account for changes in leaf area and aerodynamics.

3.3 Soil Moisture Model

de Jong (1981) reviewed many existing soil water mathematical models. He divided all the models into three groups: physically based models, soil water budgets, and combinational models. The physically based models use the principles of the continuity of soil water flow to predict water movement in response to water potential gradients. These models require a detailed data base regarding soil and plant properties. A soil moisture budget estimates soil moisture by trying to balance inflows and outflows (usually on a daily basis) of soil water within a hypothetical block of soil. Stated simply, water additions minus water losses from the soil equals the net increase in water storage within the soil. Water outflows can occur through ET, surface runoff, percolation below the root zone, and lateral subsurface flow into adjacent soil. Water inflows come from rainfall, irrigation, upward flow of water from below the root zone, surface flow, and lateral subsurface flow. Soil moisture budgets are inherently empirical. The combinational models unite concepts from soil moisture budgets and physically based models.

Neither the physically based or the combinational models are frequently used because of the need for detailed information of the plant and soil. By contrast, soil moisture budgets are almost universally used to estimate soil moisture for irrigation purposes or for hydrological models.

Soil moisture budgets vary in complexity. In their simplest form, only one soil layer is considered with rain and irrigation being the only inflow and ET the sole outflow. More complex soil moisture budgets divide the soil into several layers or zones and consider all the inflows and outflows thought to be important by the modeler.

Baier and Robertson (1966) developed the "Versatile Soil Moisture Budget" (VSMB). Baier et al. (1979) cited numerous applications where the VSMB had predicted soil moisture within the accuracy of measured "field" soil moisture.

The VSMB estimates both soil moisture and ET on a daily basis. This is done by balancing changes in soil moisture, inflows from irrigation and rain, and outflows from surface runoff, ET, and deep percolation below the root zone. All inflows are assumed to occur at the end of day after all ET has taken place.

The versatility of the VSMB stems from its ability to accommodate both homogeneous and vertically heterogeneous soils of any rooting depth. Also, the VSMB allows the user considerable scope to choose some of the functional relationships.

The VSMB divides the rooting depth into six layers or zones. Each zone represents a horizontal slice of soil of unspecified thickness. From the uppermost to the lowermost, these zones contain 5.0, 7.5, 12.5, 25.0, 25.0 and 25.0% of the total capacity for plant available moisture in the root zone. From the top of the root zone to the bottom, the zones are numbered one to six.

Empirical crop coefficients, k, reflect the amount of water extracted from each zone. The k coefficients are different at various growth stages of the crop to account for changes in rooting pattern and crop canopy. Finally, the z factor for each zone estimates the effect of soil moisture on ET. The k coefficients and z factor not only determine the distribution of ET from the root zones but also determine the relationship between Penman PET estimate and actual crop PET during different growth stages.
The equation to predict ET for each zone was:

$$ET(j) = k(j) * SM(j)/SMC(j) * z(j) * PET \qquad (3.33)$$

where:

$k(j)$ is the k crop coefficient for zone j,
$SM(j)$ is available soil moisture in zone j (mm),
$SMC(j)$ is available soil moisture capacity in zone j (mm),
$z(j)$ is the z factor for each zone,
PET is the PET estimate (mm/d).

ET from any zone was, of course, limited to SM(j).

Using the k coefficients presented in the 1979 VSMB (Baier et al. 1979) for wheat underestimated seasonal ET for irrigated wheat at Lethbridge. Scott (1975) derived crop coefficients on a calendar basis from actual soil moisture experiments in southern Alberta. The total of the Scott's k coefficients was larger than the total for the 1979 VSMB k coefficients and thus, Scott's k coefficients predict higher ET from soils with equally available moisture contents. In this study the VSMB k coefficients were modified so their root zone totals agreed more closely with those of Scott. The VSMB zonal proportions were left unchanged. For alfalfa the 1979 VSMB k coefficients were used unaltered. Table 3.5 lists alfalfa and wheat k coefficients. With no active growth the k coefficients from top to bottom were: 0.60, 0.15, 0.05, 0.0, 0.0, 0.0 (Scott 1975).

When the surface soil is dry, plants absorb comparatively more water from lower, relatively moist soil zones. The 1979 VSMB allowed for an adjustment of k coefficients to account for this behavior as follows:

$$k'(j) = k(j) + k(j) * [\sum_{m=1}^{m=j-1} k(m)*(1-AM(m))] \qquad (3.34)$$

where k'(j) is the adjusted k coefficient for zone j.

The adjustment was made to the lower four zones whenever the crop was growing and the average available moisture in the upper three zones was less than 25% of available soil moisture capacity.

Table 3.5 Crop k Coefficients

Alfalfa

Crop Growth Stage	Zone 1	2	3	4	5	6
Start of Growth to Full Cover	0.50	0.20	0.15	0.12	0.08	0.05
Full Cover to First Cut	0.50	0.25	0.23	0.22	0.15	0.10
First Cut to Full Cover	0.50	0.22	0.18	0.15	0.15	0.10
Full Cover to Second Cut	0.50	0.25	0.25	0.20	0.18	0.12
After Second Cut	0.45	0.25	0.20	0.20	0.20	0.15

Wheat

Crop Growth Stage	Zone 1	2	3	4	5	6
Planting to Emergence	0.43	0.15	0.13	0.10	0.03	0.01
Emergence to Jointing	0.47	0.23	0.16	0.14	0.03	0.02
Jointing to Heading	0.45	0.28	0.17	0.13	0.12	0.05
Heading to Soft Dough	0.40	0.31	0.22	0.18	0.15	0.09
Soft Dough to Ripened	0.40	0.29	0.20	0.15	0.07	0.04

Many relationships have been hypothesized and tested to explain the effect of soil moisture on ET. Of these relationships, many suggest that resistance to soil moisture extraction decreases solely as available soil moisture decreases (Jensen 1968, Mapp et al. 1972, Minhas et al. 1974, Rasmussen and Hanks, 1978, Rhenals and Bras 1981, Sammis et al. 1983). The VSMB has a number of z curves which predict ET as a function of available moisture. These are shown in Figure 3.1. Curves G and H are suggested for first estimates. Baier et al. (1979) point out that the choice of the z curve is somewhat arbitrary since ET predictions vary little between similar curves (e.g. D and C).

Numerous researchers have explained the degree of soil moisture extraction decreases with increasing PET and/or decreasing available moisture (Holmes and Robertson 1963, Gavande and Taylor 1967, Windsor and Ven Te Chow 1971, Dudley et al. 1971, Yang and de Jong 1972, Saxton et al. 1974, Doorenbos and Pruitt 1977, Selerio and Brown 1979). Relationships involving both AM and PET probably best describe root extraction and plant stomatal behavior.

Eagleman (1971) developed the following equation for the z factor based on experiments for alfalfa in Arizona, meadow grasses in Ohio, and corn and soybeans in Iowa:

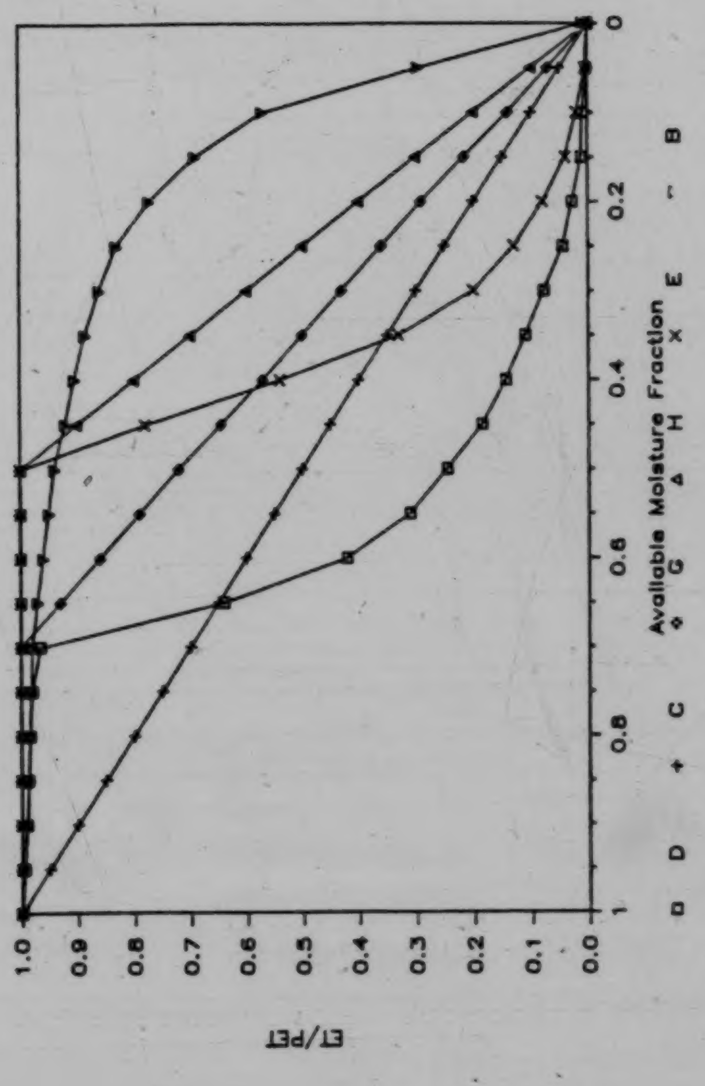


Figure 3.1 Versatile Soil Moisture Budget z Curves

$$\begin{aligned} z(j) = ((&-0.050 + 0.732/PET)/AM(j) + \\ &(3.97 - 0.661 * PET) + \\ &(-8.57 + 1.56 * PET) * AM(j) + \\ &(3.35 - 0.880 * PET) * AM(j)^2) \end{aligned} \tag{3.35}$$

where AM(j) is available moisture in zone j.

The experimental data base for equation (3.35) had PET ranging from 2.0 to 9.0 mm/d. Figure 3.2 plots z versus AM at PET equal to 2.0, 5.0 and 8.0 mm/d. Eagleman's function was used since it agreed reasonably well with the VSMB z curves but included the effect of PET on the crop's ability to extract soil moisture. Although unwieldy for hand calculation, it was relatively simple to implement on a high speed computer. Predicted z factors from equation (3.35) were limited to the range from 0.0 to 1.0.

The irrigation system was assumed to be designed such that all irrigation water infiltrates the soil surface. In addition, the VSMB assumes all precipitation less than 25.4 mm infiltrates the soil. For precipitation in excess of 25.4 mm the following equation was applied to estimate infiltration:

$$\begin{aligned} I = 25.4 * (&0.9117 + 1.811 * \ln(R/25.4) - \\ &0.97 * AM(1) * \ln(R/25.4)) \end{aligned} \tag{3.36}$$

where:

I is surface infiltration (mm),
R is daily precipitation (mm),
AM(1) is AM fraction in zone 1 (surface).

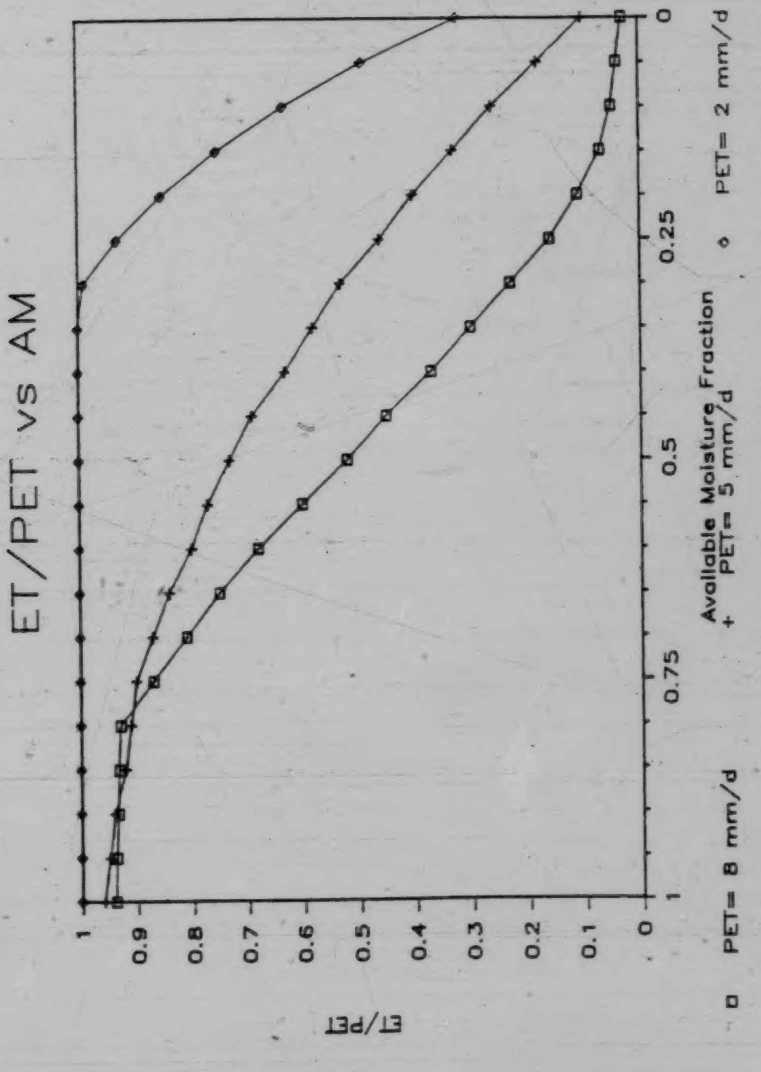


Figure 3.2 z Factor from Eagleman (1971)

Any precipitation which does not infiltrate was counted as surface runoff. The VSMB estimation technique for surface runoff is a very crude approximation since it does not take into account the surface landform or the structure and texture of the topsoil.

de Jong (1981) pointed out the major criticism of soil moisture budgets in general is that they do not account for unsaturated flow (i.e. soil moisture movement when the soil moisture content is less than field capacity). Although van Schaik et al. (1976) found the VSMB could ably model soil moisture in southern Alberta, they suggested the VSMB could be improved by allowing unsaturated flow. The 1979 VSMB contains an empirical percolation coefficient which permits downward unsaturated flow on days with rain and/or irrigation. The basic equation for percolation into the subsurface soil zones was:

$$I(j) = [(1-AM(j)) * b(j)] * (I(1) - \sum_{n=1}^{j-1} I(n)) \qquad (3.37)$$

where:

I(j) is percolation into zone j,

b(j) is the percolation coefficient for zone j.

The percolation coefficient, b, varies between 0.0 to 1.0. Baier et al. (1979) suggested b is about 0.0 for coarse coarse textured soils and about 1.0 for fine textured soils. The b coefficient applied only when AM(j) was less than 0.90.

Percolation into any zone was limited to that which will raise the zone to field capacity. After percolation into the bottom zone had been calculated, any remaining water was counted as deep percolation and was assumed to be lost permanently from the root zone.

de Jong and Shaykewich (1981) developed a soil moisture budget very similar to the VSMB. They added a modification to account for a nearly impermeable layer below the root zone. The hydraulic conductivity of this layer was given a constant value of 0.5 mm/d. Soil zones above this layer can become saturated. These saturated zones represent a perched water table. Water uptake by roots from any saturated zone did not take place unless the moisture content of the zone directly above was less than 95% of saturation.

In east central Alberta, many Solonetzic soils have a B horizon which is nearly impermeable to water or roots. Likewise some Luvisolic soils, which developed on fine textured parent material, have a nearly impermeable illuvial B horizon. To model these soils the modification of de Jong and Shaykewich was used. The z factor of the zone whose overlying layer was greater than 95% saturated was set at 0.05. When the entire root zone became saturated, all subsequent rain or irrigation became surface runoff.

de Jong and Shaykewich (1981) also presented an eauation for estimating foliar interception:

$$ITC = 1.0 + RR/[0.5 * (RR + 15.0)] \qquad (3.38)$$

where:

ITC is foliar interception (mm),
RR is rainfall and irrigation (mm).

Equation (3.38) was applied between the jointing stage and harvest for wheat and during the latter 80% of each growth of alfalfa. Interception was subtracted from PET on the day rainfall or irrigation occurred. Interception was limited to that day's PET to allow no carry-over. Evaporated interception was added onto that day's ET.

Three hypothetical soil types were modeled. All were assumed to be located on land with a level to rolling topography (0 to 8% slopes), good surface drainage, and a permanent water table below the root zone.

With no restriction, effective crop rooting depths are usually considered about 0.9 to 1.2 m for wheat and 1.2 to 1.8 m for established alfalfa (Krogman and Hobbs 1976).

Soil type I was considered to be representative of many common cultivated soils in east central Alberta. This soil was homogeneous, medium to fine textured (loam to clay loam), and had a permeable subsoil with no restriction on root depth. Because each VSMB zone contains a proportion of total plant available moisture, the assumed moisture holding properties could represent a number of combinations of rooting depths and total volumetric available moisture capacity. The modeled moisture holding properties apply to a rooting depth of wheat and alfalfa of 1.2 m and 1.5 m, respectively, with 12% total available moisture capacity, 0.9 m and 1.2 m with 16% total available moisture capacity, or 0.69 m and 0.91 m with 21% total available moisture capacity. The percolation coefficients were set at 0.5 for all zones and the hydraulic conductivity of the soil underlying the lowest zone was set at 10 mm/d. Saturation was assumed to occur when the soil contained 119% more water than available moisture capacity (Hausenbuiller 1978).

Soil type II was an attempt to represent many Solonetzic soils as well as Luvisols which developed on fine textured parent material. Effective rooting depth was restricted by a hardpan and was the same for both wheat and alfalfa. The root depths were 0.515 m with 14% total available moisture capacity, 0.400 m with 18% total available moisture capacity, or 0.333 mm with 22% total available moisture capacity. The percolation coefficient was 1.0 for all zones and the hydraulic conductivityof the restricting layer was set at 0.5 mm/d. Saturation was assumed to occur when the soil contained 89% more water than available moisture capacity (Hausenbuiller 1978).

Soil type II is not a good soil for irrigation development because it has very poor internal drainage. However, such soils are of interest because they may occur in small patches within a field of otherwise better soil.

Soil type III was designed to represent a soil which developed on coarse textured materials (sand to sandy loam). Because these soils have a limited moisture holding capacity, crops grown on them are especially subject to drought. Therefore these coarse textured soils are attractive soils to irrigate. Soil type III rooting depths for wheat and alfalfa were 1.35 m and 1.8 m respectively at 6% available moisture capacity, 0.9 m and 1.2 m at 9% available moisture capacity, or 0.675 m and 0.9 m at 12% available moisture capacity. The percolation coefficient was 0.0 for all zones (i.e. no percolation until the upper zones reached field capacity). The hydraulic conductivity of the subsoil was set at 20 mm/d. Saturation was assumed to occur when the soil contained 345% more water than available moisture capacity (Hausenbuiller 1978).

The processes of overwinter soil moisture movement and infiltration of snowmelt are poorly understood. To circumvent this problem, the moisture content of the soil profile on April 9 was generated as a random variable. Gray et al. (1983) analyzed the overwinter moisture changes of dryland and irrigated soils in central Saskatchewan. Their work showed that the post-smowmelt moisture content of the upper 0.3 m of soil was approximately uniformly distributed between maximum and minimum limits. Therefore the actual soil moisture content on April 9 was assumed to be uniformly distributed. The smallest and largest expected fraction of total available moisture capacity for the 2nd and 5th zones were inputted. The starting soil moisture was chosen randomly between these limits. The moisture content of the top zone was set equal to the second while that of the bottom zone was equal to the fifth zone. The moisture contents of the third and fourth zones were interpolated between the second and fifth zones. For soil types I and III, which had good internal drainage, if a moisture content greater than field capacity was generated, it was set to field capacity. This adjustment was not made to soil type II, thus, allowing a very wet soil immediately following snowmelt.

Preliminary model runs showed that on October 15, irrigated soils frequently contained considerably more soil moisture in the soil profile than the dryland soils. To account for this, separate April 9 soil moisture limits for irrigated and dryland soils could be inputted. The randomly generated fraction between the maximum and minimum soil moisture limits for zone 2 was the same for both irrigated and dryland soil. This assumed that soil moisture in both the irrigated and dryland topsoil were highly correlated. For soil zone 5, soil moisture was generated independently for the dryland and irrigated soils.

Table 3.6 lists the assumed limits on the proportion of available soil moisture for each location, crop, and soil type. The moisture limits for wheat attempted to simulate the starting soil moisture for a crop planted equally often

Table 3.6 Maximum and Minimum Proportions of Plant Available Soil Moisture Capacity for Wheat and Alfalfa

		Topsoil		Subsoil	
Soil		Maximum Propor. AM Cap.	Minimum Propor. AM Cap.	Maximum Propor. AM Cap.	Minimum Propor. AM Cap.
		Alfalfa			
I	Black	1.00	0.25	0.50	0.25
	Dark Brown	1.00	0.10	0.50	0.00
II	Black	1.00	0.50	1.00	0.00
	Dark Brown	1.00	0.50	0.90	0.00
III	Black	1.00	0.25	0.50	0.25
	Dark Brown	1.00	0.10	0.50	0.00
		Wheat			
I	Black	1.25	0.50	1.00	0.25
	Dark Brown	1.00	0.50	1.00	0.25
II	Black	1.25	0.50	1.00	0.25
	Dark Brown	1.25	0.50	1.00	0.25
III	Black	1.25	0.50	1.00	0.25
	Dark Brown	1.00	0.50	1.00	0.25

on stubble and fallow soil. de Jong and Cameron (1980) reported that grain stubble on Dark Brown soils in Saskatchewan gain an average of 82 mm of moisture from harvest to after snowmelt (standard deviation was 35 mm). Fallow Dark Brown soils gain an average of 115 mm with a standard deviation of 33 mm from harvest to the next seeding. For grain stubble Black soils in Saskatchewan the gain was 57 mm with a standard deviation of 45 mm while for fallow Black soils the moisture gain was 63 mm with a standard deviation of 45 mm. However it was assumed that Black soils (Edmonton and Lacombe) would be slightly more moist in the spring than the Dark Brown soils (Coronation and Lethbridge) because the Black soil zone generally receives more fall and winter precipitation along with less PET than the Dark Brown soil zone. Also the Black soils were assumed to have slightly more available moisture at harvest than the Dark Brown soils. For both Black and Dark Brown soil type II the starting soil moisture in the spring for wheat had the same distribution because it was assumed that this soil's low moisture storage capacity and poor internal drainage would balance out the differences between the Black and Dark Brown soil zones. A larger difference between spring soil moisture for the Black and Dark Brown soil zones was assumed for hayland. The rationale for this latter assumption was that not only does the Dark Brown soil zone receive less precipitation, but generally growth continues farther into the fall in the Dark Brown soil zone so there is less moisture in the root zone when the stand becomes dormant in the fall. Table 3.7 lists the assumed probability distribution of spring stored moisture for all soils which were modeled.

To simplify the running of the model, the starting soil moisture for the irrigated soils was normally the same as the dryland moisture distribution listed in Table 3.7.

Table 3.7 Probability Distributions of Stored Soil Moisture on April 9

	Stored Soil Moisture on April 9 (mm)					
Probability of	I		II		III	
Exceeding	Bl	Dk Br	Bl	Dk Br	Bl	Dk Br
			Alfalfa			
1.0	48	6	11	11	27	3
0.9	56	17	17	16	31	10
0.8	63	29	23	22	36	16
0.7	71	44	29	27	40	23
0.6	78	53	35	33	44	33
0.5	86	65	41	39	48	36
0.4	94	77	47	44	35	43
0.3	101	88	54	50	57	50
0.2	109	100	60	56	61	56
0.1	116	112	66	61	65	63
0.0	124	124	72	67	70	70
			Wheat			
1.0	47	47	23	23	26	26
0.9	57	56	29	29	32	32
0.8	68	66	34	34	38	37
0.7	79	76	39	39	44	43
0.6	90	86	45	45	50	48
0.5	101	95	50	50	57	54
0.4	111	105	56	56	63	59
0.3	121	115	61	61	68	65
0.2	129	125	66	66	72	70
0.1	136	134	72	72	77	77
0.0	144	144	77	77	81	81

3.4 Alfalfa

Alfalfa (Medicago sativa) is grown as a forage for ruminants in a wide variety of climates. Alfalfa has no period of heightened sensitivity to moisture stress. Alfalfa is drought tolerant and can become almost dormant during prolonged drought periods. Much of its drought tolerance, however, comes from its extensive root system which can draw water from considerable depths. In Alberta, alfalfa is often grown in mixtures with any of a number of different grass species. These alfalfa-grass mixtures improve both forage and livestock productivity and also improve stand longevity. Alfalfa is a legume and thus can supply much of its nitrogen needs using atmospheric nitrogen with the aid of symbiotic microorganisms. Other than fertilizer requirements (alfalfa-grass mixtures typically need more nitrogen than more pure stands of alfalfa), the management and use of alfalfa-grass mixtures with at least 50% alfalfa is very similar to pure alfalfa. Although alfalfa is a perennial, the proportion of alfalfa in the stand decreases each year because of winterkill of the alfalfa and the competition from other plants. After several years (usually four to ten years) the stand must be plowed under. Usually in the establishment year (the year seeded), only one or no cut is taken. Alfalfa or alfalfa-grass mixtures can be utilized as dry hay, dehydrated feed, pasture, or haylage.

Bauder et al. (1978) in North Dakota and Daigger et al. (1970) in Nebraska both found that seasonal alfalfa yield is an approximately linear function of seasonal consumptive use. Other work has suggested that the yield response of alfalfa to consumptive use, rather than being linear, decreases as seasonal consumptive use increases (Alberta Agriculture 1982). Bauder et al. (1978) also found that the ratio of actual alfalfa yield to potential yield (moisture not limiting) is proportional to the ratio of actual seasonal consumptive use to potential seasonal consumptive use. Stewart and Hagan (1969) concluded a similar relationship holds in central California.

Holt et al. (1978) developed SIMED which is a elaborate computer simulation model of alfalfa growth. SIMED attempts to predict material flow, growth, respiration, and water relations in an alfalfa crop on a hourly basis. SIMED requires extensive hourly weather data in addition to detailed modeling of many internal plant processes.

3.4.1 Alfalfa Development Model

Selirio and Brown (1979) estimated that alfalfa in southern Ontario begins growing after the daily mean temperature exceeds 5 °C for five days after March 15. Wilcox and Sly (1975) suggested that effective growth of alfalfa in western Canada begins on the third day of five consecutive days when the mean daily temperature exceeds 5.6 °C. Another criteria for estimating the growing season of alfalfa is the period between the last spring frost and the first fall frost. The temperatures of a killing frost is often taken as -2.2 °C (Pohjakas et al. 1967).

In the model, spring growth was assumed to start on the first day after 40 degree days (5 °C base) had been attained providing the minimum temperature on that day was greater than -2.2 °C. Growth occurred on each day the temperature was greater than -2.2 °C. After the first cut the first frost below -2.2 °C caused the stand to go dormant until the subsequent spring.

The date of the cutting of alfalfa is a variable determined by the farmer based on the weather, crop condition, and other demands on available labour and machinery. Optimum quality and the yield of alfalfa are achieved by cutting during the early bloom stage. Selirio and Brown (1979) predicted early bloom occurs after 550 degree days (5 °C base) have been accumulated since the start of growth or cutting. Doorenbos and Kassam (1979) estimated alfalfa is ready for harvest after 500 to 550 degree days (5 °C base) have been accumulated. For the model, the lowest value (500 degree days) was used since in the sunny climate of Alberta alfalfa will mature at a rapid rate.

Irrigated and dryland alfalfa were assumed to develop at identical rates. This simplified the model but was actually a poor assumption. Heywood et al. (1972) noted that, in the Edmonton region, dryland alfalfa began flowering earlier than irrigated alfalfa. One of the irrigators contacted in the study region used irrigation partly to delay alfalfa flowering to control quality. The effect of assuming equal development rates on yield is probably not great over two cuts.

3.4.2 SIMFOY Alfalfa Yield Model

SIMFOY (Selerio and Brown 1979) is a soil moisture based yield model developed to predict dry matter forage yields for crop insurance purposes in southern Ontario. Although SIMFOY is claimed to be applicable for all types of forage including pasture, it is based on alfalfa and alfalfa-grass mixtures.

Cumulative potential yield was calculated from:

$$P = Q/(1 + EXP(5.3 - 6.7 * SQRT(D))) \qquad (3.39)$$

where:

P is cumulative potential growth,

Q is maximum cumulative yield for each growth (12 000, 7 000, and 5 000 kg/ha for the first, second, and third growths, respectively),

D is the alfalfa development index for each growth (D increases linearly with degree days and equals 0.0 at start of growth or regrowth and 1.0 when ready for cutting).

If harvested when D equals 1.0 then the potential yields from each growth are 9626, 5615 and 4011 kg/ha (total 19252 kg/ha). Daily potential growth for the current day (day i) was simply the difference between the current cumulative potential growth and that for the previous day:

$$p(i) = P(i) - P(i-1) \qquad (3.40)$$

where p(i) is daily potential growth on day i.

Growth occurs at the potential rate only if available soil moisture throughout the root zone exceeds 80% of field capacity. If the available moisture in all or part of the root zone is below 80%, then daily growth is reduced by the ratio of actual available moisture, weighted for root distribution, to 0.8. The relevant equations were:

$$y(i) = p(i); \quad ASM(i) > 0.8 \tag{3.41}$$

$$y(i) = p(i) * ASM(i)/0.8; \quad ASM(i) < 0.8 \tag{3.42}$$

where ASM(i) is the total of AM for each zone multiplied
by a weighting factor for root distribution
for each zone.

SIMFOY contains its own soil moisture budget which assumes a homogeneous soil with a rooting depth of 0.75 m. The budget divides the root zone into six zones which from the uppermost to the bottommost contain 10, 10, 20, 20, 20, and 20% of the total available moisture capacity, respectively. SIMFOY was adapted to the VSMB by adjusting the rooting distribution to the standard VSMB zones. The adjusted weighting factors for each zone during different development stages are given in Table 3.8.

Applying SIMFOY to a root zone exceeding 0.75 m would increase the estimated yields because each zone contains more moisture. Thus, for the same moisture extraction, the soil moisture content would remain higher and less yield reduction would take place.

Table 3.8 SIMFOY Root Weighting Factors Converted to VSMB Zones

Crop Growth Stage	VSMB Zone 1	2	3	4	5	6
First Growth						
0.0 < D < 0.1	0.200	0.275	0.275	0.200	0.050	0.000
0.1 < D < 0.2	0.175	0.250	0.275	0.200	0.088	0.013
0.2 < D < 0.3	0.150	0.213	0.250	0.238	0.088	0.063
0.3 < D < 0.4	0.125	0.188	0.250	0.263	0.113	0.063
0.4 < D < 0.5	0.125	0.175	0.200	0.225	0.150	0.125
D > 0.5	0.100	0.150	0.200	0.250	0.175	0.125
Second and Third Growths						
D < 0.2	0.175	0.250	0.275	0.200	0.088	0.013
D > 0.2	0.100	0.150	0.200	0.250	0.175	0.125

3.4.3 Wageningen Alfalfa Yield Model

The Wageningen yield model is a standard crop production model. The Wageningen method has been applied to a wide variety of field crops. Essentially the model estimates total plant dry matter production based on the assimilation of carbon dioxide using available energy from the sun. As with other crop models, the Wageningen method ignores the effect of diseases, insect pests, parasites, and weeds on yield. The Wageningen yield model also assumes optimum soil fertility (i.e. the availability of micronutrients and macronutrients does not impose any restriction on yield). The above assumptions are reasonable with appropriate choice of crop rotations and crop variety along with the use of effective pesticides and fertilizer application based on recommendations stemming from laboratory soil fertility tests.

The basic equation of the Wageningen yield method is:

$$y = K * Cp * Ct * Cs * Hi * Pst * ET/(Ea-Ed) \qquad (3.43)$$

where:

y is daily dry matter production (kg/ha),

K is a crop dependent constant reflecting water use efficiency,

Cp is photosynthetic efficiency,

Ct is correction for mean daily temperature,

Cs is the correction for active leaf area, Hi is the proportion of total dry matter growth which is harvested,

Pst is daily photosynthetic flux from available solar energy (kg/ha),

ET is daily evapotranspiration (mm),

(Ea-Ed) is mean daily water vapour pressure deficit (mb).

Slabbers et al. (1979) used this method with average growing season values for all factors. They compared predicted yields with measured yields for trials on four continents, which included data from Vauxhall, Alberta. They could explain 92% of the observed variation of alfalfa yields.

Slabbers et al. (1979) presented plots of the response of alfalfa to mean daily temperature. The temperature correction Ct, was estimated from these plots. The equations for the first and for subsequent growths were:

1st growth: $$Ct = -0.43610 + 0.130775 * Tmean - 0.0028296 * Tmean^2 \qquad (3.44)$$

2nd and 3rd growths: $$Ct = -1.28706+0.180495*Tmean- 0.00355*Tmean^2 \qquad (3.45)$$

These relationships are plotted in Figure 3.3. The temperature correction was limited to the range from 0.0 to 1.0. Pearson and Hunt (1972) confirmed that Canadian alfalfa cultivars produce more growth as the mean daily temperature is increased from 10 °C to 20 °C.

The equation used to estimate Hi as a function of total cumulative yield (t/ha) was (Slabbers et al. 1979):

$$Hi = 0.28572 + 0.321513 * Y - 0.067883 * Y^2 + 0.0063318 * Y^3 - 0.00212327 * Y^4 \qquad (3.46)$$

This equation is not valid for the establishment year of the alfalfa stand. The relationship is plotted in Figure 3.4.

Feddes et al. (1978) suggested the soil cover increases exponentially until leaf area index LAI (i.e. the total leaf area divided by the underlying soil area), reaches 5.0 after which Cs equals 1.0. Research by Nelson and Smith (1964) and Krogman and Hobbs (1965) showed that complete soil cover is achieved about halfway through each growth. The following equation was used to estimate the soil cover factor:

$$\begin{aligned} Cs &= EXP(1.4 * D) - 1.0 && \text{if } D < 0.5 \\ Cs &= 1.0 && \text{if } D > 0.5 \qquad (3.47) \end{aligned}$$

where D is alfalfa development index from equation (3.39)

The measurements of LAI of alfalfa by Nelson and Smith showed that LAI during the first growth is somewhat higher than that in subsequent growths. To allow for this, the Cs

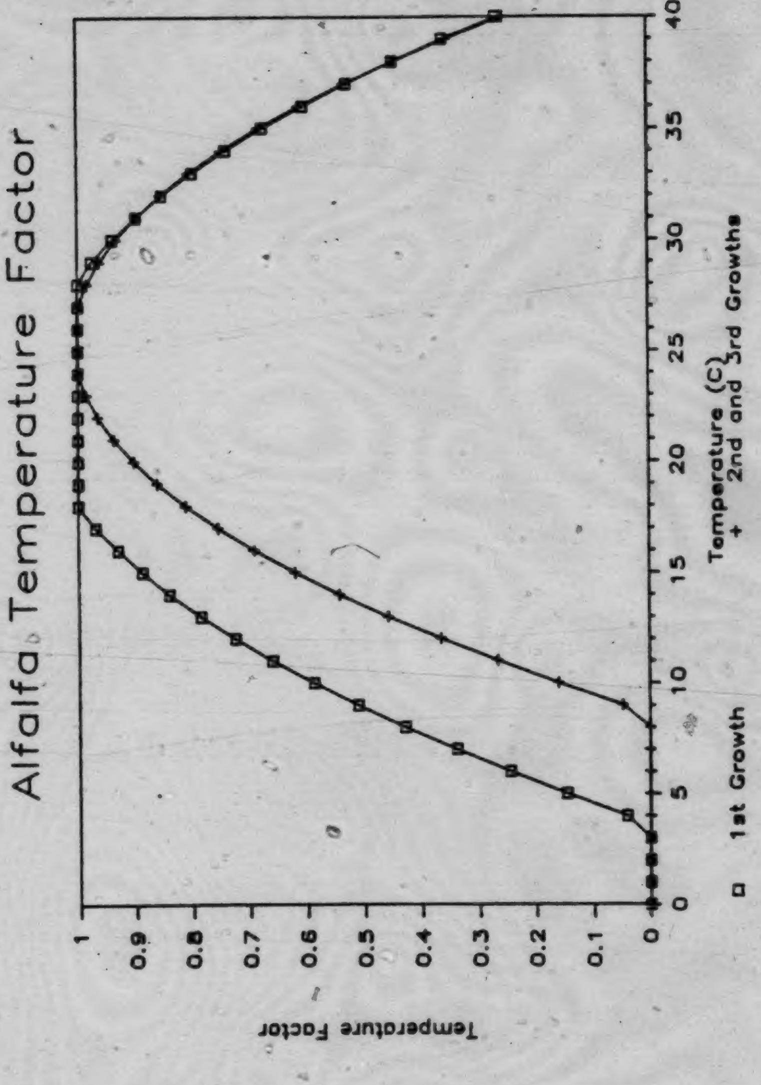


Figure 3.3 Temperature Correction Factor for Alfalfa

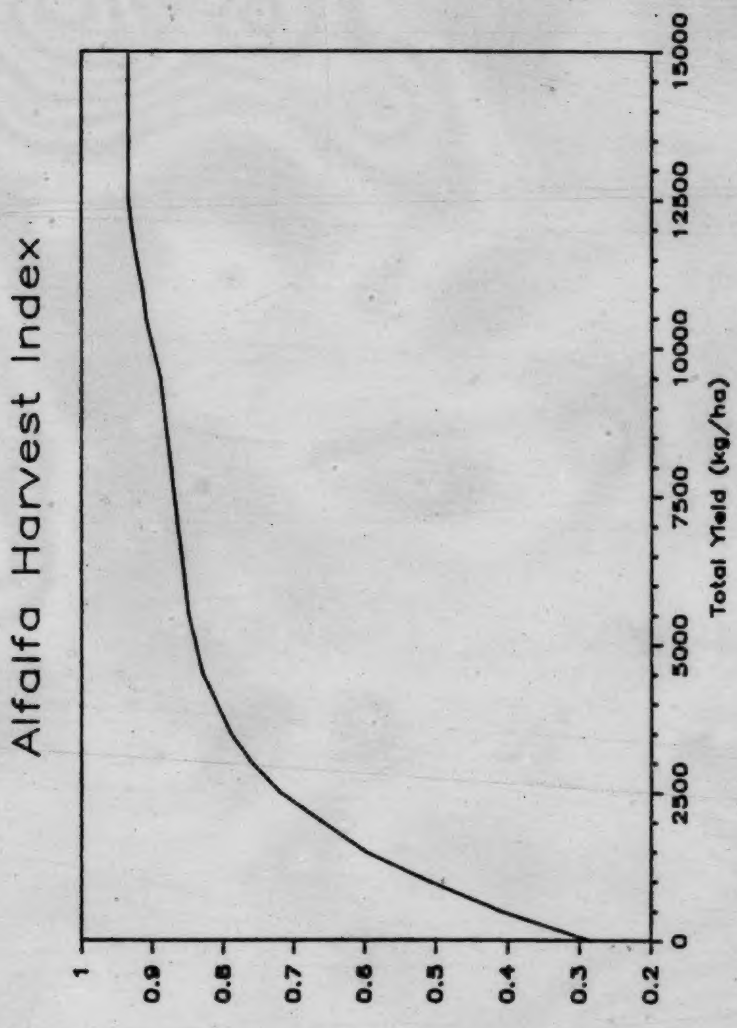


Figure 3.4 Harvest Index for Alfalfa

calculated by equation (3.47) was multiplied by 0.9 after the first growth. The soil cover factor versus crop development is plotted in Figure 3.5.

The value of the crop water use constant, K, was given as 0.9 by Doorenbos and Kassam (1979), but as 1.0 in Slabbers et al. (1979). This latter value was used. The photosynthetic efficiency, Cp, of alfalfa was 0.6. (Slabbers et al. 1979, Doorenbos and Kassam 1979).

The photosynthetic flux was calculated from:

$$Pst = F * Po + (1 - F) * Pc \tag{3.48}$$

where:

F is the proportion of the day which is overcast,

Po is photosynthetic flux on a overcast day (kg/ha),

Pc is photosynthetic flux on a clear day (kg/ha).

Feddes et al. (1979) presented tabulated values of Po and Pc on the 15th of each month for a number of latitudes. These values were estimated for 40, 50 and 60 °N by:

$$Po = 18.81 + 0.06956 * Ro * (3.0+SIN(Lat)) \tag{3.49}$$

$$Pc = 80.326 + 0.12148 * Ro * (3.0+SIN(Lat)) \tag{3.50}$$

where Ro and Lat as in equation (3.26)

The overcast proportion of the day, F, was estimated from PET and Ro. First, atmometer latent evaporation was estimated from PET. Then hours of bright sunshine were

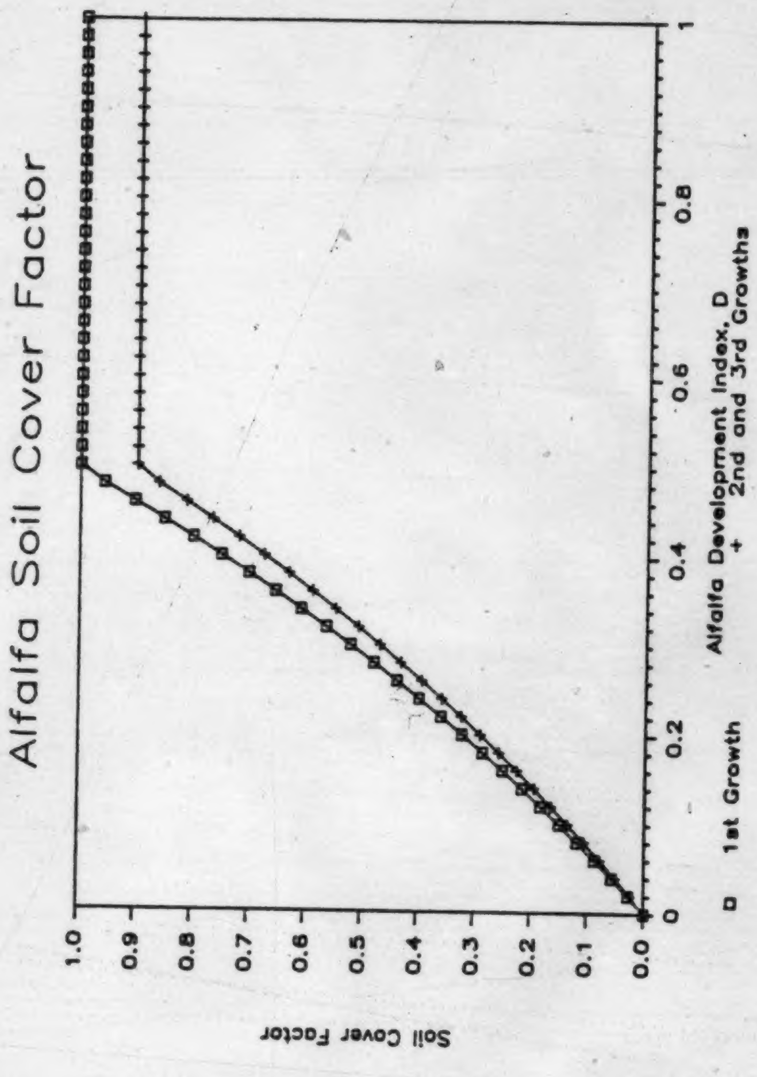


Figure 3.5 Soil Cover Correction Factor for Alfalfa

estimated from Baier and Robertson's (1965) equation for latent evaporation calculated from daily maximum and minimum temperatures, measured hours of bright sunshine, and solar radiation at the top of the earth's atmosphere. The final equation was:

$$F = [(((0.50 - PET)/0.0763) - 55.67 + 0.687 * Tx + 0.284 * (Tx - Tn) + 0.0263 * Ro)/Ro + 0.0594]/0.0422 \qquad (3.51)$$

where:

Tx is the daily maximum temperature (°F),
Tn is the daily minimum temperature (°F).

F was limited to the range from 0.0 to 1.0.

Water use efficiency, WUE, is the harvested yield divided by total consumptive use. In the Wageningen method WUE is inversely proportional to the atmospheric vapour pressure deficit. Table 3.9 gives mean monthly water vapour pressure deficits for several Alberta points. As would be expected, with similar crop seasonal consumptive use (CU), equation (3.43) predicted seasonal yields which were approximately inversely proportional to June, July, and August vapour pressure deficits. This gave Edmonton an approximately 15% higher WUE than Coronation and a 30% higher WUE than Lethbridge (mean temperatures and sky clearness also affect WUE). Hence, even after allowing for the smaller CU at Lethbridge and Coronation, equation (3.43) imparted a substantial yield advantage to Edmonton.

Table 3.9 Mean Monthly Atmospheric Water Vapour Pressure Deficit (mb) for Several Alberta Locations'

Location	May	June	July	August	Sept.
Medicine Hat	6.7	8.3	10.7	10.0	6.2
Lethbridge	5.6	7.5	9.4	8.4	5.7
Calgary	5.1	6.3	7.3	6.4	4.6
Coronation	5.1	6.1	6.9	6.0	3.8
Red Deer-Penhold	5.1	5.5	5.7	4.7	3.5
Edmonton	5.2	5.6	4.8	4.2	3.0
Vermilion	5.1	5.5	5.4	4.5	3.1
Grande Prairie	5.3	6.0	6.1	5.2	3.3

1) Calculated from climatological data in: Atmospheric Environment Service, Canadian Climate Normals 1951-1980: Pressure, Temperatures and Humidity, Vol. 8, Environment Canada, Downsview, Ontario.

WUE is most frequently measured for grain crops. There is no evidence to support the idea that WUE is directly proportional to the reciprocal of vapour pressure deficit. de Jong and Cameron (1980) reported that WUE of spring wheat in Saskatchewan is about the same in the Blacksoil zone (which has a climate with generally small vapour pressure deficits) as in the Brown soil zone (which has a climate with generally large vapour pressure deficits). Peters and Pettapiece (1981) found that barley WUE may be higher in southern Alberta (where relatively large vapour pressure deficits prevail) than in central and northern Alberta. They discovered that barley, grown on similar soils and in areas with similar moisture conditions, yields 10% more south of a east-west line through Red Deer than north of this line. Obviously, assuming WUE is inversely proportional to water vapour pressure deficit as the Wageningen method) is a gross simplification of real crop behavior.

Theoretically, WUE can be expressed as (Feddes et al., 1978):

$$WUE = K' * [(Cl-Ca) * (Rwa + Rwl)] / [(Ea-Ed) * (Rca + Rcl + Rcm)] \qquad (3.52)$$

where:

K' is a crop dependent constant,

$(Cl - Ca)$ is the difference between carbon dioxide concentration within the leaf and that in the atmosphere,

Rwa is the boundary layer resistance to diffusion of water vapour,

Rwl is the leaf (i.e. stomatal) resistance to diffusion of water vapour,

Rca is the boundary layer resistance to diffusion of carbon dioxide,

Rcl is the leaf (i.e. stomatal) resistance to diffusion of carbon dioxide, Rcm is the mesophyll resistance to diffusion of carbon dioxide from intercellular air into the cells.

For the Wageningen method the carbon dioxide concentration gradient and the ratio of the resistances to diffusion of water vapour and carbon dioxide are assumed constant so equation (3.52) becomes:

$$WUE = K/(Ea - Ed) \tag{3.53}$$

where K is the crop parameter as in equation (3.43).

Slabbers et al. (1979) reported that both leaf and mesophyllic resistance to diffusion of carbon dioxide increases as leaf turgor decreases. This, in turn, suggests the ratio of diffusion resistances in equation (3.52) decreases as crop moisture stress increases. As discussed earlier, with soil at the same moisture content, leaf turgor will tend to decrease as PET increases. This implies WUE may be inversely proportional to PET.

The Penman equation predicts that PET increases as wind speed rises. The boundary layer resistances to diffusion of water vapour or carbon dioxide depends on crop physical shape and wind speed. With the same crop shape, increasing the wind speed reduces boundary layer resistances. Inspecting equation (3.51) indicates that decreasing the boundary layer resistances would decrease WUE. Again this suggests that WUE may be inversely proportional to PET.

With solar radiation and wind speeds held constant, the Penman PET estimate is proportional to the atmospheric water vapour pressure deficit. Therefore Penman PET integrates the effects of vapour pressure deficit with other atmospheric conditions which may affect WUE. As the atmospheric effects on WUE are poorly understood, a hypothesis was made that daily WUE was inversely proportional to Penman's PET estimate rather than water vapour pressure deficit per se. By coincidence, for many climates, including east central Alberta, the numerical value of both the daily range of PET (expressed as mm/d) and vapour pressure deficit (expressed as mb) are very similar. Also Penman PET and vapour pressure deficit are positively correlated. Hence, yields calculated using the Wageningen method assuming WUE is inversely proportional to vapour pressure deficit, are similar to yields calculated with a modified Wageningen method assuming WUE is inversely proportional to PET. Therefore it is not inconceivable that validation experiments showing the value of the Wageningen method would still hold true for a modified Wageningen method assuming WUE is inversely proportional to PET.

Assuming that WUE was inversely proportional to Penman PET produced a modified Wageningen method. The basic equation of the modified Wageningen method for predicting daily yield was:

$$y(i) = K'' * Cp * Ct * Cs * ET(i)/PET(i) \qquad (3.54)$$

where:

K" is a constant reflecting WUE,
Cp, Ct, Cs, and ET(i) as in equation (3.43),
PET(i) is Penman PET on day i.

The K constant in equation (3.43) includes a proportionality constant with units of mb/(mm/d). The K" constant for equation (3.54) contains a proportionality constant with units of (Penman mm/d)/(mm/d). It was assumed that the numerical value of both the above constants was identical.

Stewart and Hagan (1969) and Bauder et al. (1978) used the following equation to predict seasonal alfalfa yields:

$$Y = P * ET/PET \qquad (3.55)$$

where:

Y is actual seasonal yield,
P is potential yield with moisture not limiting,
ET is seasonal ET,
PET is seasonal PET.

Equation (3.55) indicates yield is inversely proportional to PET. In the modified Wageningen method, P is not a constant as in equation (3.55) but a value determined by temperatures, sky conditions, and the number of days of active growth during the year.

Since the harvest index (Hi) changes throughout the year as cumulative growth increases, Hi was calculated and applied only to cumulative growth. Alfalfa hay is safe for storage at moisture contents below 20% (wet basis). The predicted dry matter yield from equation (3.54) was multiplied by 1.18 to convert the yield to 15% moisture content.

Seasonal yield was multiplied by a management factor, M. This factor accounts for the effects of farming practices, weeds, pests, and diseases on yield. The effect of weather during haying on yield quantity and quality was not considered.

Alfalfa stores food reserves in its roots in the fall. Without these reserves the alfalfa is more likely to die. Hence, if the second growth is poor, the alfalfa may not have sufficient food reserves if the second cut is taken. Arbitrarily, then, if the yield from the second cut was less than 1100 kg/ha (15% m.c.), it was assumed the cut was not taken.

3.5 Wheat

Wheat (Triticum aestivum) can be grown as either a winter or a spring crop. As a winter crop, it is planted in late summer or early fall. After initial growth the crop goes dormant over the winter and resumes growth in the spring. Winter wheat is a risky crop in east central Alberta because cold spells in the winter can kill many or most of the plants. For this reason almost all the wheat grown in east central Alberta are spring varieties which are seeded in the year they are harvested.

Spring wheat varieties are divided into hard varieties and soft (durum) varieties. Hard wheat is subdivided into bread and utility (feed) varieties. Bread wheat varieties contain a higher proportion of protein than the other types of wheat. Generally speaking, bread wheat varieties attain the highest protein content (and thereby highest grade and price) when moisture is limiting. However, bread wheat can also attain high protein contents when moisture is not limiting if there is plentiful available nitrogen in the soil. Soft and utility varieties produce more grain per unit of water consumed than bread wheat. Therefore they yield best under humid conditions.

Wheat is quite drought tolerant and can adapt to moisture stress throughout its growth cycle. Moisture stress during the vegetative growth phase (up to heading) results in less straw weight and fewer heads (because there are fewer tillers). Moisture stress during flowering (10 to 15 days after heading) results in fewer grain kernels per head. During grain filling (end of flowering to hard dough stage) kernel weight is reduced. Grain yield is the product of number of heads, kernels per head, and kernel weight.

Wheat prefers warm daytime temperatures but cool nighttime temperatures. Mean daily temperatures of 15 to 20 °C with ample moisture are optimum during the vegetative growth phase. No growth occurs when the mean daily temperature is 5 °C or less (Doorenbos and Kassam 1979). During final ripening, dry warm weather is preferred. Very high temperatures during flowering reduce yields.

Wheat is most sensitive to moisture stress during the flowering stage. The next most sensitive period is the grain filling stage followed by the vegetative growth stage. During final ripening wheat is almost insensitive to moisture stress (Bauer 1971, Doorenbos and Kassam 1979, de Jong and Cameron 1980, Kirkam and Kanemasu 1983).

Wheat is best suited to medium to fine textured soils with a permanent water table more than one metre below the soil surface (Doorenbos and Kassam 1979). Wheat responds well to fertilizer additions. Optimum management entails balancing fertilizer application with anticipated moisture consumptive use.

Army et al. (1959) found yield of winter wheat in Texas could be best predicted by a quadratic equation involving growing season precipitation. Ehlig and LeMert (1976) could explain 96% of the yield variation of winter wheat in California using a cubic equation involving total applied moisture.

Williams (1969) analyzed wheat production for individual Statistics Canada crop districts in western Canada. He attempted to predict average district yields from estimates of soil moisture before May 1 and both precipitation and PET for the months of May, June, and July. Generally he found good agreement between predicted and known yields. He calculated separate regression coefficients for each crop district.

Bauer (1971) conducted an extensive survey of the literature on the effect of the amount and timing of precipitation and amount of spring-stored moisture on wheat yields in the Northern Great Plains of North America. He presented a number of linear regression equations which relate yields to soil moisture in the spring and precipitation over the growing season. The resulting equations varied with location, soil texture, and whether planted on fallow or stubble. Generally wheat yields increase with increasing growing season precipitation and/or increasing spring stored soil moisture.

Lehane and Staple (1965) compared yields of many plantings of wheat grown on clay, loam, and sandy loam soils at Swift Current. They found the best correlation existed when spring soil moisture below 0.3 m depth was included with precipitation totals during each 15 day period from May 1 to August 31. This regression explained 67% of the yield variation for a loam soil but only 40% for the sandy loam soil.

Robertson (1974) analyzed 50 years of wheat yields at Swift Current. He considered monthly averages of pan evaporation, daily maximum and minimum temperatures, and daily solar radiation at the top of the earth's atmosphere. These were combined in a rather complex fashion. Robertson was able to account for about 73% of the variation in wheat yields.

Baier and Robertson (1967a) tried to relate wheat yields from plot trials across Canada to estimates of available moisture during a number of crop growth stages. Generally the regression equations could explain less than 60% of the variation in wheat yields. They concluded it is important to include the effects of temperature on yield. In a later analysis Baier and Robertson (1968) found that yield was correlated closer to daily maximum and minimum temperatures than to rainfall. However they found a regression based on available moisture estimates better explained yields than the combination of maximum and minimum temperatures with precipitation. Baier (1973) analyzed the wheat yield trials and developed a "crop-weather-analysis model" from a complex regression analysis. The crop-weather-analysis model uses daily maximum and minimum temperatures, daily estimates of ET/PET, and a daily estimate of relative crop development. This model was capable of predicting 77% of variation in wheat yields -- a high value considering the data set included 79 plantings at eight widely separated sites across Canada. Unfortunately, the model regression coefficients have been misplaced and are probably unretrievable (Baier, personal correspondence, 1983). A concerted effort was made to estimate the regression coefficients from plots of the functional relationships found in Baier (1973). However, the crop-weather-analysis model proved to be too sensitive to the coefficient values for successful resurrection of the model in this fashion. Another attempt was made to modify the estimated coefficients so they conformed to an intuitive understanding of wheat yield response to environmental factors. Again, a workable wheat yield model based on the crop-weather-analysis model could not be formulated.

Neghassi et al. (1975) could predict 75% of the variation in winter wheat yields in Nebraska using an equation involving ET to PET ratio during several growth stages. Minhas et al. (1979) could accurately explain wheat yield trails at Delhi, India with another yield function which was based on ET to PET ratios during several periods during the growing season. Rasmussen and Hanks (1978) used another model based on the ratio of estimated actual transpiration to potential transpiration during several growth stages. They could explain 98% of the variation in grain yields from a limited set of spring wheat trials in Utah.

Yaron et al. (1973) developed several yield relationships based on the number of days during different growth periods when soil moisture was below a specific amount. Haun (1974) assembled a rather complicated mathematical model to predict average spring wheat yields over large areas. He calculated a number of growth factors for 10 day periods from May 2 to July 30. These growth factors depended on maximum temperature, minimum temperature, and estimated available moisture. The model was calibrated using plot data from North Dakota. This model provided good estimates of yields in the USSR but poorer estimates of provincial wheat yields in Canada. In particular, wheat yields in Alberta were underestimated.

3.5.1 Wheat Development Model

No attempt was made to accurately model the seeding process. Instead germination (i.e. start of growth) was assumed to take place following four days with tractable soil (to allow for planting) providing 70 degree days (5°C base) had accumulated since April 9 (to allow for adequate soil warmth).

Soil tractability criteria were taken from Dyer et al. (1978). For coarse textured soils (soil type III), the moisture content in the upper two zones must be less than 95% of their respective available moisture holding capacity. The moisture content of the next lower zone must be less than 98% of its available moisture holding capacity. For medium to fine textured soil (soil types I and II), the moisture content of the upper three zones must be less than 90% of their moisture holding capacity. The moisture content of the irrigated soil was used to determine soil tractability for seeding.

Robertson (1968) developed a biometeorological time scale for hard spring wheat which related crop physiological development to daily maximum and minimum temperatures and hours of daylight. The time scale was derived from many years of plot trials across Canada. Williams (1974) provided a clear explanation of how to implement Robertson's wheat time scale.

The basic equation of Robertson's time scale was:

$$PS = (V_1 * (V_2 + V_3)) \tag{3.56}$$

where:

PS is a value indicating crop phenological development (ranging from 0.0 to 5.0),

V_1 is a daylength factor,

V_2 is a maximum daily temperature factor,

V_3 is a minimum daily temperature factor.

Each V factor was calculated separately each day from:

$$V_1 = a_1 * (DL - a_0) + a_2 * (DL - a_0)^2 \qquad (3.57)$$

where:

a_1, a_2 are regression constants,

a_0 is a threshold daylength (hours) derived from regression analysis,

DL is the number of hours between sunrise and sunset.

$$V_2 = b_1 * (Tx - b_0) + b_2 * (Tx - b_0)^2 \qquad (3.58)$$

where:

b_1, b_2 are regression constants,

b_0 is a threshold temperature (°F) derived from regression analysis,

Tx is daily maximum temperature (°F).

$$V_3 = b_3 * (Tn - b_0) + b_4 * (Tn - b_0)^2 \qquad (3.59)$$

where:

b_3, b_4 are regression constants,

b_0 as in equation (3.58),

Tn is daily minimum temperature (°F).

The daily hours of bright sunshine was estimated from (Muir, 1979):

$$DL = 2/15 * Ws \qquad (3.60)$$

where Ws is the sunrise angle as in equation (3.28)

Whenever the daily temperature was below the threshold temperature the corresponding V factor was set to zero. Since phenological development is an irreversible process, if any of the V factors became negative it was set to zero.

There are six benchmark development stages: planting (PS = 0), emergence (PS = 1), jointing (PS = 2), heading (PS = 3), soft dough (PS = 4), and ripe (PS = 5). Ripe is defined when the crop is approximately ready for swathing rather than ready for straight combining. For each of the five periods between the six benchmark stages, a separate set of regression constants and threshold values applies. The regression constants and threshold values were those given by Robertson (1968).

3.5.2 Wageningen Wheat Yield Model

The Wageningen model, very similar to that used for alfalfa, was used to predict wheat yields. As with alfalfa, crop water use efficiency was assumed to be proportional to Penman PET rather than atmospheric vapour pressure deficit. The basic equation to estimate daily growth was:

$$y = M * K * DC * Cp * Ct * Cs * Hi * Pst * ET/PET \qquad (3.61)$$

where:

M is a management factor accounting for the effect of farming practices, weeds, pests, and diseases on yield,

K is a constant reflecting water use efficiency and has a value of 1.17 (Doorenbos and Kassam 1979),

DC converts dry matter yield to 14.5% m.c. and has a value of 1.17,

Cp is constant accounting for photosynthetic efficiency and has a value of 0.6 (Doorenbos and Kassam 1979),

Ct is a factor accounting for the effect of daily mean temperature on yield,

Hi is the proportion of total plant weight which is harvestable grain,

Pst is the daily photosynthetic flux as calculated using equation (3.48) (kg/ha),

ET is the estimated actual daily ET (mm/d),

PET is the Penman PET estimate (mm/d).

The temperature factor was estimated from tabulated values in Doorenbos and Kassam (1979). The following equation includes the photosynthetic efficiency of 0.6:

$$Ct = -0.33 + 0.102 * Tmean - 0.00234 * Tmean^2 \qquad (3.62)$$

This relationship is plotted in Figure 3.6.

The polynomial expression developed by Stewart (1981) was used to predict LAI (leaf area index) of spring wheat. This expression was based on a growing season of 130 days and was:

$$LAI = 6.691 - 0.9106 * GL + 0.0390 * GL^2 - 6.529\ E\text{-}04 * GL^3 + 4.463\ E\text{-}06 * GL^4 - 1.257\ E\text{-}08 * GL^5 \quad (3.63)$$

where GL is cumulative growing time (days).

Since spring wheat varieties grown in Alberta mature in less than 130 days, the actual growing time was normalized to 130 days. The following equation was used to accomplish this:

$$GL = 130 * PS/5.0 \quad (3.64)$$

where PS is crop development stage from equation (3.56).

The soil cover factor was estimated from:

$$Cs = LAI/5.0 \quad (3.65)$$

Figure 3.7 presents a plot of the wheat soil cover factor of wheat as a function of crop development.

Doorenbos and Kassam (1979) estimated that the proportion of total growth devoted to grain varies between 0.3 and 0.4. Stewart (1981) found the lowest possible value of Hi pertaining to the agro-ecological zone yield method (which is closely related to the Wageningen method)

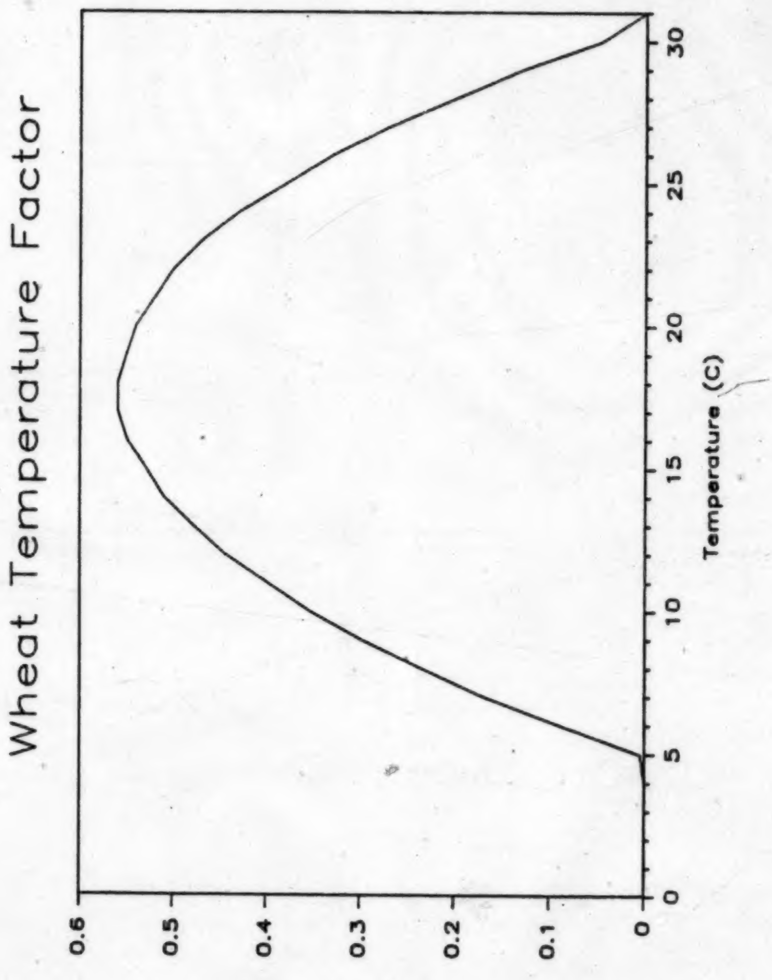


Figure 3.6 Temperature Correction Factor for Wheat

worked satisfactorily for predicting wheat yields in Canada. Based on this, Hi was set at 0.3. Although it is reasonable to postulate that Hi would be a function of moisture stress, there is no evidence in the literature to support this conjecture. Korven and Wiens (1974) measured straw and grain yields for irrigation trials at Swift Current. There was no discernible trend linking the ratio of grain yield to the sum of straw and grain yield with either total yield or moisture conditions.

Crops which are grown for their fruit typically respond differently to moisture stress at different crop growth stages. As mentioned earlier, wheat is particularly sensitive to moisture stress during the flowering stage as well as during the yield formation stage. The response to moisture stress was approximated by:

$$Y = P * MSF \qquad (3.66)$$

where:

Y is actual seasonal yield,

P is potential seasonal yield with no moisture stress,

MSF is the moisture stress factor.

The moisture stress factor was estimated from:

$$MSF = 1 - ky(j) * (1 - ET(j)/PET(j)) \qquad (3.67)$$

where:

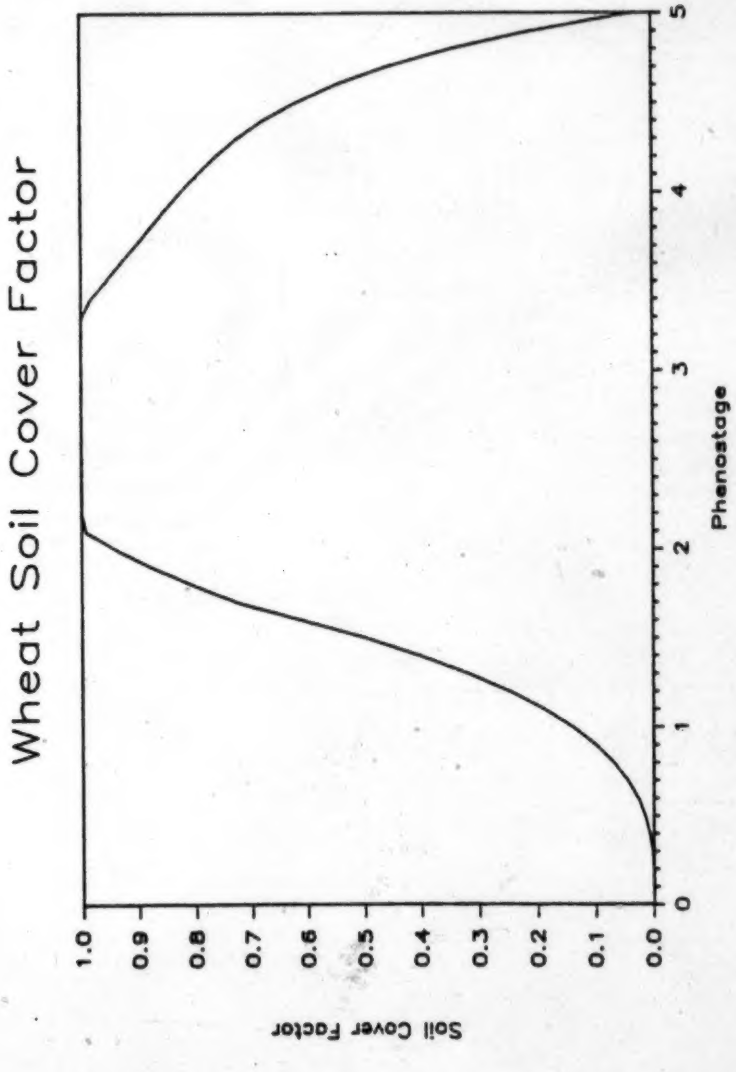


Figure 3.7 Soil Cover Correction Factor for Wheat

ky(j) is a constant expressing crop sensitivity to moisture stress during growth period j,

ET(j) is actual ET during growth period j,

PET(j) is potential crop ET during growth period j.

Doorenbos and Kassam (1979) gave values 0.7 to 1.0 to ky during vegetative growth (up to heading), 2.5 to 4.0 during flowering, and 1.5 to 2.0 during yield formation. The average growing season value for ky can be taken as 1.15.

Equation (3.61) contains an implicit ky of about 1.0 because actual yield varies linearly with the ratio of ET to Penman PET. Penman PET as calculated by equation (3.16) is a reasonable estimate of crop PET during the flowering and yield formation stages but is greater than crop PET during other growth stages. To convert the Wageningen ky values to the modified Wageningen method, the ky values for equation (3.67) were reduced by 1.0.

The equation to calculate the seasonal MSF was:

$$MSF = (\sum(1 - ky(j) * (1 - ET/PET)))/GSL \qquad (3.68)$$

where:

MSF as in equation (3.67) except that it is limited to the range between 0.0 and 1.0,

ky(j) as in equation (3.67) except it is reduced by 1.0,

ET is daily ET (mm/d),

PET is daily Penman PET (mm/d),

GSL are the number of days of active growth

In a wheat field, flowering lasts for about 10 days after heading starts. This was estimated as the period between PS equal to 3.0 to PS equal to 3.5. The yield formation stage was assumed to last from PS equal to 3.5 to PS equal to 4.5. Outside of these two periods ky was set at 0.0. Any wheat variety recommended for Alberta must have good drought tolerance. Therefore the lowest values of ky from Doorenbos and Kassam (1979) were used. After being reduced by 1.0, ky was 1.5 and 0.5 for the flowering and yield formation stages, respectively.

The final total yield equation was:

$$Y = M*MSF*K*Hi*Cp*DC*\sum(Cs*Ct*Pst*ET/PET) \quad (3.69)$$

where:

M, K, Hi, Cp, DC, Cs, Ct, Pst, ET, PET as in equation (3.61),
MSF as in equation (3.67).

The effect of harvest weather on yield quantity and quality was not considered. Hard frosts (<-2.5 °C) were considered to cause complete crop loss if they occurred between the jointing and soft dough stages. Before the jointing stage, the growing part of the wheat plant remains below the soil surface so the crop is not greatly damaged by frosts. Hard frosts between the hard dough stage and swathing were assumed to halt further growth but not affect cumulative yield.

3.6 Irrigation Systems

3.6.1 Irrigation Scheduling Model

The crop growing period was divided into five stages. These stages are listed in Table 3.10. The stages listed in Table 3.10 were used in the VSMB for determination of the appropriate k coefficients. For irrigation scheduling purposes, these five stages wereadvanced Table 3.11 lists the five irrigation scheduling crop growth stages.

Irrigation scheduling was based on soil moisture in the root zone. The minimum and desired quantity of available moisture were input for each irrigation scheduling crop growth stage. The irrigation scheduling crop growth stages were advanced so that some or all of the irrigation water could be applied before a particular phenological crop growth stage was attained. For example, consider irrigation with a side roll which has a irrigation interval of 14 days. To maintain the soil above a desired depletion level for any crop growth stage, irrigation would have to be

Table 3.10 Crop Growth Stages

Growth Stage		Description
		Wheat:
1	(PS = 0 to 1)	planting to emergence
2	(PS = 1 to 2)	emergence to jointing
3	(PS = 2 to 3)	jointing to heading
4	(PS = 3 to 4)	heading to soft dough
5	(PS = 4 to 5)	soft dough to ripe (swathing)
		Alfalfa:
1	(PS = 0 to 0.5)	start of growth to full cover
2	(PS = 0.5 to 1)	full cover to first cut
3	(PS = 1 to 1.5)	start of regrowth to full cover
4	(PS = 1.5 to 2)	full cover to second cut
5	(PS > 2)	after second cut

Table 3.11 Irrigation Scheduling Crop Growth Stages

Growth Stage		Description
		Wheat:
1	(PS = 0.0 to 0.75)	planting to pre-emergence
2	(PS = 0.75 to 1.75)	pre-emergence to pre-jointing
3	(PS = 1.75 to 2.75)	pre-jointing to pre-heading
4	(PS = 2.75 to 3.75)	pre-heading to pre-soft dough
5	(PS = 3.75 to 4.5)	pre-soft dough to hard dough
		Alfalfa:
1	(PS = 0.0 to 0.375)	start of growth to pre-full cover
2	(PS = 0.375 to 0.875)	pre-full cover to pre-first cut
3	(PS = 0.875 to 1.375)	pre-first cut to pre-full cover
4	(PS = 1.375 t0 1.875)	pre-full cover to pre-second cut
5	(PS > 1.875)	after pre-second cut

started before that crop growth stage was reached. Otherwise, AM in the last part of the field to be irrigated may not be brought above the desired depletion until the crop has passed through the growth stage.

The assumption was made that no irrigation in excess of crop moisture need was required to leach salts below the root zone to maintain a favourable salt balance in the root zone. Irrigation was permitted between the beginning and ending cut-off dates which were inputted for each program run.

On the Canadian Prairies, alfalfa does not usually respond to irrigation before early June (Korven and Kilcher 1979). Therefore, irrigation of alfalfa was not normally started until June 1. Irrigation was not permitted from a few days before the cutting of the alfalfa hay (D = 0.95) until seven days after cutting. This was to allow time to remove the baled hay from the field. However the effect of haying weather on cutting date and on the time needed to remove the hay from the field was not considered. In southern Alberta, fall irrigation is promoted to replenish the soil moisture reserves for the following spring (Alberta Agriculture 1981b). Fall irrigation in east central Alberta is probably of less benefit because autumn weather is not as dry in terms of precipitation and PET as in southern Alberta. Consequently, irrigation of alfalfa was stopped after the pre-second cut stage (PS=1.875).

Irrigated wheat does not respond to irrigation during the final ripening period (Krogman and Hobbs 1976). Therefore, irrigation of wheat was stopped when the crop reached the approximate hard dough stage (PS=4.5). Most irrigators delay irrigation until the initial spraying of post-emergence herbicides has been completed. Thus, normally irrigation of wheat was not started until the pre-jointing stage (PS=1.75). In east central Alberta, this stage was not reached until the second or third week of June.

The number of VSMB soil zones used to estimate soil moisture for irrigation scheduling purposes varied with the crop development stage. During growth stage 1 of alfalfa, only the upper five zones were used for soil types I and III. During the other alfalfa growth stages all six zones were considered. Because of its shallow root zone, all zones were considered for alfalfa on soil type II. On soil types I and III the upper 3, 4, 5, 6, and 6 zones were considered for growth stages 1 through 5 of wheat, respectively. On soil type II the upper 4, 5, 6, 6, and 6 zones were used for growth stages 1 through 5 of wheat, respectively.

The maximum seasonal water supply was inputted as the maximum net application depth over the entire irrigated area. When this seasonal supply was depleted such that there was insufficient water for one complete irrigation, the system was shut off for the season.

The operation of the irrigation systems was highly idealized. Labour for irrigation was always available, there were no system breakdowns, the application was both uniform and precisely known, and water was always available until the seasonal supply was exhausted. In addition the irrigator had perfect knowledge of soil moisture.

3.6.2 Centre Pivot Systems

About one-third of the irrigated land in Alberta is irrigated with centre pivots (Purnell 1982). The area irrigated with centre pivots is growing more rapidily than any other irrigation method. Some of this growth is the result of farmers changing from other irrigation methods.

The modeled stationary centre pivot (SCP) had a 400 m long lateral which would irrigate 53 ha in one revolution. Irrigation started whenever the actual available moisture (AM) dropped below the minimum allowed moisture amount for the proportion of the root zone considered for the specific crop growth stage. The planned application depth was the difference between the desired and actual moisture contents. If the planned depth exceeded the maximum possible with the remaining water supply, then the planned amount was reduced to conform to the water supply limitation. If there was insufficient water to complete one revolution at the fastest permissible revolution rate, then no more irrigations were possible.

The maximum and minimum revolution rate were inputted for each model run. Thus, either a water drive or electric drive pivot could be modeled. The model attempted to apply the water at the revolution rate midway between the maximum and the minimum. For planned irrigation depths greater than that which can be applied in one revolution at the minimum revolution rate, two or more revolutions were used. The minimum application depth was equal to that applied with one revolution at the maximum revolution rate. Generally, the actual irrigation application equaled the planned irrigation depth. An irrigation was defined as a series of uninterrupted revolutions.

The modeled soil was a thin strip underneath the lateral when the irrigation was started. With revolution rates less than one per day, it was possible for this strip not to be irrigated even if the system was irrigating that day. Likewise, with revolution rates exceeding one per day, this strip could be irrigated more than once per day. The model kept track of where the lateral was at the beginning and end of the day. Hence, it was a simple matter to determine how many times the modeled strip was watered that day.

Two sizes of towable centre pivots (TCP) were modeled: i) with a 400 m long lateral irrigating 53 ha in one revolution, and ii) with a 220 m long lateral irrigating

15 ha per revolution. Once set up in the field which required irrigation, the towable pivots were operated exactly as a stationary pivot. Two of three irrigated positions (circles) could be modeled for a towable pivot. At the beginning of the season, the pivot was always located in field one. With the system idle, field one had priority over field two which in turn had priority over field three. If the field in which the pivot was located did not require irrigation then an attempt was made to move the pivot to the lowest numbered field which required irrigation. The pivot could only be moved if the soil in the field where the pivot is located contained tractable soil. Soil tractability criteria were those used for estimating when wheat was seeded. With tractable soil, one entire 24 hour day was needed to move and set up the pivot at its new location. An irrigation was defined as an uninterrupted series of irrigations at one position.

With light rains it was possible for the surface to be untractable and yet have the total available moisture undesirably depleted at the same position (especially if the allowable depletion was small). In this case the other positions would likely be more depleted. However the position where the pivot was located was irrigated first. Thus it was possible for one position to be irrigated two or more times in succession.

The model tallied the labour required for irrigation. Labour requirements were based on one person-hour per day when irrigating and ten person-hours to move and set up the pivot (Ring, personal communication 1984).

All the pivots applied water at a rate sufficient to apply 15 mm per day on soil types I and III and 10 mm per day on soil type II. The application efficiency was set at 80% (Ring personal communication 1984).

3.6.3 Side Roll and Hard Hose Reel Traveller Systems

Side rolls (also called wheel rolls or wheel moves) are used on about one-third of the irrigated land in Alberta (Purnell 1982). The modeled side roll had either one or two 400 m long laterals. The crop and soil irrigated by only one lateral was modeled. Therefore, the only real difference between a one and two lateral system was the fixed irrigation costs. The sets were located 20 m along the mainline so that each set was 0.8 ha. The lateral required 0.7 h for one person to move it to a new set (Korven and Randall 1975). The application rate was set so that 50% of total available moisture capacity was applied in one eight hour set (including moving time). Therefore the maximum application rate was 13 mm/h for alfalfa on soil type I and the minimum was 5 mm/h on soil type II. The application efficiency was set at 75% (Ring, personal communication 1984).

Hard hose reel travelers have only been recently introduced in Alberta and are not common. Hard hose travelers were developed in Europe for supplemental irrigation -- especially for irregularly shaped fields. A hard hose traveler consists of a large gun sprinkler with a wetted diameter of 60 to 180 m. The gun moves continuously in strips or sets which extend outward from the main supply line. The gun moves continuously along these strips while a non-collapsible supply hose is reeled in automatically.

The modeled hard hose reel traveler (HHT) consisted of one gun with a 400 m long hose. The sets were located 80 m along the mainline so that each set was 3.2 ha. It was assumed the average time needed to move the gun between sets was 1.5 h. The hard hose traveler applied 50% of total available moisture capacity in one 24 hour set (including moving time). The application efficiency of the hard hose traveler was assumed to be 80% (Ring, personal communication 1984).

Irrigation scheduling was based on the available moisture in the first (starting) set. Since the application rate is fixed by system design, the irrigation time for a set was varied to adjust the application depth. The maximum and minimum number of sets per day were inputted. This prevented the system from attempting to use unrealistically short or long sets. If there was insufficient water supply to allow the entire field to be irrigated at the minimum set time, the system was shut off for the season.

Because it can take many days for a side roll or hard hose traveler to irrigate the entire field, there is a high probability that some rain will fall during that time. A total of the rainfall which fell since the irrigation started or restarted was kept. Only 90% of the rainfall above 5.0 mm was considered to infiltrate the soil. Whenever this rainfall total equalled or exceeded 25% of the planned irrigation depth, irrigation was interrupted. Irrigation was restarted when this rainfall had been consumed. The assumed use rate was 85% of average PET on a dry day for the current weather generation ten day period.

The model kept track where the system was at the beginning and end of each day and thereby could determine which modeled position, if any, was irrigated that day. On the day the irrigation was finished, the lateral or traveler unit was immediately moved back to the starting position. However, a new irrigation could not be started until the next day.

3.7 Economics

The basic approach used to evaluate the economical feasibility of irrigation was to estimate the average annual net returns which could be expected with irrigation. The net returns were defined as the difference between gross revenues resulting from irrigation and the costs which can be attributed to irrigation. The gross revenue was the dollar value of the difference between irrigated yield and dryland yield. The annual costs due to irrigation were the sum of average depreciation, average interest charges, pumping costs, labour costs, incremental fertilizer costs, harvesting costs for the yield increase, and repair and maintenance costs of the irrigation equipment. The total annual irrigation costs subtracted from the gross revenues equals the net revenues or net returns.

Many costs were assumed to be identical for both the irrigated and nonirrigated land -- land costs, property taxes, biocide costs, tillage costs, and seeding costs. In the Black and Dark Brown soil zones, this is probably a reasonable assumption with regard to land costs, biocide costs, and seeding costs (Hamlin 1983a). In the drier areas of the Dark Brown soil zone and in the Brown soil zone this is not a good assumption for grain crops. Here biocide costs for irrigated crop production may be up to three times higher per hectare than for dryland crop production and recommended dryland seeding rates are less than irrigated seeding rates (ECA 1982). Usually, irrigated land is assessed at a higher tax rate than nonirrigated land. However the increased land taxes would not be large relative to other costs associated with adopting irrigation and may be ignored without affecting the economics greatly. Because there are more crop residues with an irrigated crop, more tillage is usually needed to prepare a good seedbed for the next crop. However, if the dryland farmer does not continuous crop, he/she pays for tillage during the fallow year -- a cost the irrigating farmer does not need to pay. With alfalfa, there would be little difference in tillage costs.

Because of the expected greater level of production, hail insurance for an irrigated crop is larger than for a dryland crop. However, this cost is relatively small and may be neglected without significantly affecting the economic analysis.

Because growth is not limited by moisture shortages, irrigated crops can use more nutrients than dryland crops. The extra fertilizer costs for irrigated production were estimated from general fertilizer recommendations for dryland and irrigated crops in Alberta (Farm Business Management Branch 1981). Table 3.12 shows the increased fertilizer requirements expressed in kg/ha and in $/ha based on fertilizer prices of $0.54/kg of elemental nitrogen and $0.69/kg of phosphate (Hamlin 1983a).

Fertilizer recommendations for the Dark Brown soil zone were used for all soil types at Coronation and Lethbridge. At Edmonton and Lacombe, Black soil fertilizer recommendations were used for soil types I and III while Thin Black recommendations were applied to soil type II. Assumed fertilizer rates for wheat were the average of fallow and stubble.

Irrigation costs were estimated from the Irrigation Cost Guide for Alberta (Ring 1984). Costs were broken down into annual fixed costs (i.e. average annual depreciation charge and average interest charge based on an annual interest rate of 13%), maintenance and repair costs, pumping costs, labour costs (based on a labour cost of $6/h), and costs to pump water to the field level. The fixed costs were increased by 10% for the side roll and the hard hose traveler to account for extra costs of increased pumping capacity and piping needed to bring water to field level. The fixed costs for the centre pivots were increased by 5% to account for the above extra costs. The capital cost of the towable centre pivot covering 15 ha in one revolution was taken from Lyster (1984). The other costs for this system were assumed to be the same as those for the larger towable centre pivot.

Table 3.13 lists the assumed irrigation costs. The pumping costs include the assumed costs of bringing water

Table 3.12 Increased Fertilizer Requirements with Irrigation

	Dark Brown Soil			Thin Black Soil			Black Soil		
	N	phos.	Tot.	N	phos.	Tot.	N	phos.	Tot.
	kg/ha		$/ha	kg/ha		$/ha	kg/ha		$/ha
Wheat:									
Stubble	20	25	21	10	20	19	5	10	10
Fallow	50	15	37	45	15	35	40	10	29
Alfalfa:	15	55	46	15	50	44	15	45	39

to field level. All the irrigation costs are general. The real costs faced by the irrigating farmer will depend on the situation of the water supply, development costs for the water supply, and the exact irrigation equipment purchased.

All pumping costs are based on using diesel fuel ($0.29/L) as a energy source for pumping. Electricity or natural gas are much less expensive if connections to the electric power grid or natural gas supply mains can be made easily. In many cases, the pumping site may be far removed from the power grid or supply mains. Where large power needs are required, such as centre pivot irrigation, three-phase electric power is necessary. Three-phase power is not widely supplied in rural areas. Diesel engines can be used from the smallest to largest pump power requirements. For a supplemental irrigation project, the pumping plant may be moved between several locations. A

Table 3.13 Irrigation Fixed and Variable Costs

System	Total Capital ($)	Annual Capital ($/yr)	Repair & maint. ($/yr)	Pumping ($/ha/mm)	Labour ($/ha/mm)
Side roll (1 lat.)	29 500	5 600	400	0.387	0.055
Side roll (2 lat.)	40 000	7 600	500	0.387	0.055
H. H. T.	48 000	8 500	1 500	0.602	0.034
Tow. C. Piv. (220 m)	48 000	7 900	1 100	0.417	0.029
Stat. C. Piv. (400 m)	76 000	12 200	1 000	0.417	0.017
Tow C. Piv. (400 m, 2 pos.)	100 000	16 500	1 500	0.417	0.029
Tow C. Piv. (400 m, 3 pos.)	106 000	17 500	1 700	0.417	0.029

towable diesel powered pumping station or a pump driven from the PTO of a diesel tractor are well suited for the latter situation.

The pumping cost to bring water to field level was estimated from the pumping costs differences between low and medium pressure sprinkler systems. This cost was $0.008/ha-mm per m of total dynamic head. For all systems, it was assumed 15 m of total dynamic head must be overcome to bring the water to field level. This would underestimate the pumping costs when water must be pumped far or raised a considerable distance.

Maintenance and repair costs were assumed constant from year to year. This is a simplification since, in reality, these costs will not likely be the same each year. There was no direct charge for water which is the case for holders of licenses for supplemental irrigation. Variable costs were calculated based on the net ha/mm of water applied each year.

To simplify the model, the fixed costs were assumed constant regardless of the land area irrigated with the side roll or hard hose traveler. The assumed costs were based on 32 ha per side roll lateral and 32 ha per traveler unit. Where the irrigated land areas are significantly less than the above values, the fixed costs would be overestimated. Similarly, where each unit irrigates more land area, the fixed costs would be underestimated. This assumption would not affect total irrigation costs greatly.

Baled alfalfa hay was valued at $80/t (Statistics Branch 1984). Because of the greater yields, harvesting the irrigated crop would involve greater wear on machinery and require more labour and fuel than harvesting the same area of dryland crop. The cost of harvesting the hay and hauling the hay to farm storage was estimated from custom rates for large round bales (600 to 700 kg per bale). It is very difficult to accurately estimate the extra harvesting costs which are entailed in harvesting the extra irrigated production. The Farm Business Management Branch

(1983) recommended that a farmer who does custom work in addition to his/her own needs should only charge the proportion of fixed machinery costs which custom work constitutes of total machinery usage. For grain and hay harvesting operations, fixed costs account for about 75% of total machine operating costs (Farm Business Management Branch 1983). The assumption was made that irrigation will approximately double yields and, therefore, only 50% of fixed machinery costs should be included in the harvesting cost for the extra irrigated production. This implies about 60% of the custom rate would be equal to the incremental harvesting costs of the yield increase due to irrigation. The harvesting charge was $9/t for windrowing, conditioning, baling, stacking, and hauling based on a dryland alfalfa yield of 2 tonnes per acre. This cost was based on typical custom rates for central Alberta (Farm Business Management Branch 1984).

Because hay is primarily fed near to where it is grown, the price of hay varies with the local forage supply and demand. In dry years, many cattle producers may require additional feed, so the price of hay can rise. In these years an irrigating producer will reap the greatest benefit from irrigation. On the other hand, in moist years, there may be an oversupply so the price of hay on the marketplace may fall. The assumption was made that the price of hay remains constant and there was always a ready market for hay.

The price of wheat was set at $185/t. Incremental harvesting costs were calculated for wheat using the approach employed for hay. The assumed dryland yield was one tonne per acre and it was also assumed irrigation will approximately double yields. Harvesting costs (swathing, combining, and hauling grain to storage) was set at $14/t based on custom rates for central Alberta (Farm Business Management Branch 1984).

The Canadian Wheat Board buys nearly all wheat grown in western Canada. A quota delivery system is used to give all producers the opportunity to market their wheat. The quota system was designed for dryland farmers and discriminates against the intensive grain producer. Under the Canadian Wheat Board quota delivery system, quantities which can be delivered to the elevator are partly based on the farmer's land area. However the irrigating producer can produce more from a given land area than a nearby dryland farmer. The irrigating producer may have difficulty selling his/her crop in some years and thus may be faced with higher storage costs per unit of production than dryland farmers. Hamlin (1983d) estimated, however, there will likely be few marketing problems (beyond those normally expected for dryland production), providing no more than 25% of the farm land area is used to produce irrigated grain.

As defined, the annual net return is an artificial entity and bears no relation to actual cashflow. Negative net returns usually mean that the weather was good for dryland crops. However, the irrigating producer would also have excellent crops. Therefore, negative net returns do not mean the irrigator will have insufficient revenues to be able to meet his/her financial obligations. Negative net returns indicate the extra expected revenues with irrigation are not as great as the extra costs incurred with irrigation. Therefore, if long-term average net returns are negative, then the weather is consistently such that irrigation is not worthwhile except as a form of drought insurance.

The net returns are only meaningful relative to dryland crop production. The returns expected from conventional dryland farming should be added onto predicted net returns from irrigation. Therefore, if dryland farming is very profitable, negative net returns from irrigation may be possible without the whole operation being unprofitable. Of course, if dryland farming is unprofitable, then positive net returns from irrigation do not guarantee that crop production will be profitable.

Using the net returns as a measure of economic viability is a form of break-even analysis. A predicted long-term average annual net return of zero means that the irrigation will just break even economically (i.e. the average revenues from irrigation will just balance the average costs of irrigation).

Studying average net returns is not an often used or particularly valid method of determining the economical feasibility of an investment. The weaknesses of this method are that tax effects and the timing of actual revenues and expenses are ignored. However, better methods of evaluating the long-term profitability of an investment require detailed information concerning the financial situation of the farm business (Gardner et al. 1981). Therefore, studying net returns from a partial budget analysis was an appropriate technique to estimate the general economic feasibility of irrigation in east central Alberta.

Irrigation involves a large capital expenditure per hectare and large operating expenses per hectare each year. At the same time the potential revenues from irrigation are also large. Therefore, irrigation would usually affect income taxes. The impact would likely be different for each farmer. If the whole of crop production is irrigated, then taxes would be positively correlated with annual net returns, as defined. The situation is more complex when only part of the farm is irrigated (as would be more likely in east central Alberta). If predicted net returns are usually positive, irrigation would increase increase income taxes paylable. In this case the estimated net returns would be overestimated. However, if net returns are negative, this would indicate revenues are less than expenses. These expenses could be written off against income earned from the rest of the farm or from income earned in other years. Hence, the predicted net returns would be lower than that actually incurred by the farmer. In years with good dryland crops, the extra revenue from irrigation production would increase taxes. Conversely, in years with poor dryland crops, the expenses of farming the dryland portion of the farm could be written off against the revenues from the irrigated production.

The capital cost allowance for the irrigation equipment can represent funds available to the farmer (since it is not a real cash expense). This income tax deduction may be particularly important in years when prices for farm products are depressed. In these years, the farmer may be able to exist, in part, on the capital cost allowance of the irrigation system. Up to a set maximum, the farmer can choose the amount of capital cost allowance for the irrigation system which is claimed as an expense for tax purposes. Therefore, the large capital cost allowance of the irrigation system can be used as a tool to reduce taxes in years when the farmer has a large net income.

Even after considering the above discussion on tax effects, though, where irrigation increases farm net income, taxes will undoubtedly consume a portion of the net returns as defined in this study. Therefore, where net returns are attractively large, the net returns would probably be overestimated.

Implicit to the concept of average annual net returns is that both the variable irrigation costs and crop prices rise at identical rates. If crop prices do not rise as quickly as the variable costs (pumping costs, fertilizer costs, costs for repair and maintenance, labour costs, and extra harvesting costs) then the average returns wouldll be overestimated. This is because returns in future years would be less than present returns. Of course, the converse is possible. If crop prices rise faster than variable irrigation costs then the average returns would be underestimated. Another assumption which affects the distribution of net returns over time is that the farmer who adopts irrigation instantaneously becomes a competent irrigation farmer. Actually it would likely require some time to acquire irrigation expertise and until this happens the net returns would likely be overestimated.

For the first year of irrigation, the lack of expertise and the initial startup costs generally create an unfavourable cashflow situation. Revenues for the first year will not be realized until after the harvest. Linsley (1983) strongly recommended that a farmer should have a substantial amount of available working capital before investing in irrigation.

The success of irrigated farming is more sensitive to management than dryland farming (Hamlin 1983d). Unless all elements of crop production (fertilization, weed control, timeliness of field operations, and water application) are well managed, irrigation farming is not likely to the profitable. The large costs for irrigation usually increase the farm debt to equity ratio after the transition to irrigation is made. Therefore, especially in the first few years of operation, irrigation may increase the farmer's financial vulnerability. Any farmer contemplating supplemental irrigation should consider this potentially detrimental influence.

If a new sprinkler irrigation system is purchased, the federal business investment tax credit (BITC) could be a consideration. In east central Alberta the BITC would be worth at least 7% of the purchase price of a new irrigation system (the exact rate varies depending on where the farm is located in Alberta). The BITC can be used to directly reduce federal income taxes. The BITC can reduce federal income taxes paid in previous years or to reduce taxes payable in the current year or in future years. Even if the farmer has insufficient federal income taxes against which to apply the BITC, the farmer is still eligible to receive a portion of BITC directly from the federal government. The BITC can significantly reduce the effective cost of the irrigation system and thereby decrease annual fixed costs.

The harvesting cost and irrigation cost both include a charge for labour. If the farmer supplies the labour himself/herself then these labour costs will not be real cash expenses.

In the short term, irrigation can appear economically feasible if the variable costs of irrigation are covered by the revenues. However, in the long term, the fixed costs of irrigation must also be paid for by the revenues from irrigation. Otherwise, when the irrigation system reaches the end of its useful life (about 15 years), the farmer can not afford to invest in new equipment to continue irrigation (unless he/she pays for the new irrigation equipment out of other sources of income).

The net return, as defined in this study, is a very simplistic measure of economic performance. All the costs and crop prices are general. Because the net returns are only relative to dryland production, they have little relation to real net returns. Despite this, the net returns have a general usefulness. Although the exact value of the net returns is only a rough indication of real net returns, the relation of the value of the net return to zero is meaningful. If the average value of the net returns is negative, then the potential irrigator should evaluate that irrigation investment carefully. Negative average net returns would suggest that the monetary benefits of irrigation over conventional dryland farming are insufficient to pay for the long-term costs of irrigation.

The economic effects of irrigation extend beyond the farm boundaries. Irrigated agricultural is more intensive and stable than dryland agriculture. Therefore, many of the economic benefits stemming from irrigation are collected by non-farmers. A study of the Eastern Irrigation District in southern Alberta, showed that about 13% of the economic benefits of irrigation go to farmers, 22% to others in the local area, 31% to others in the province, and 34% to others in Canada (ECA 1982). Presently the province of Alberta pays 84% of the costs of rehabilitating the water delivery works of the irrigation districts. Farmers (through the irrigation districts) must pay the remaining 14%. The rationale for this division is that the farmers receive only about 14% of the economic benefits of irrigation.

Widespread irrigation opens up many business and employment opportunities. Hamlin (1983c) noted most rural municipalities in Saskatchewan lost a significant proportion of their population in the last 20 years while a few municipalities have retained their population or recorded modest increases. The only rural municipality to experience a substantial rise in population was the municipality of Outlook which contains the South Saskatchewan River Irrigation District. Irrigation in this district first started in the late 1960's.

The Environmental Council of Alberta conducted a study of irrigation in Alberta (ECA 1982). They concluded that irrigation farming must be subsidized if it is to be viable in the long term. Presently, irrigation farmers organized into irrigation districts receive subsidies in the form of government assistance to rehabilitate the existing water supply network and the construction of new capital works. The Enviromental Council recommended that private irrigators (those not members of a irrigation district) should also receive subsidies. In east central Alberta, irrigation development would almost certainly be composed of private projects. In Saskatchewan, the provincial government offers grants up to $247/ha (up to a maximum of $50 000 per farm) to assist dryland farmers develop private irrigation projects (Saskatchewan Agriculture 1984).

In Alberta, Alberta Agriculture and the Prairie Farm Rehabilitation Administration (PFRA) both provide technical assistance for the planning and design of irrigation projects at no charge to the farmer. PFRA also offers financial assistance -- one third of the project cost up to a maximum of $2200 per farm.

4.0 Results and Discussion

Two output files were created by the program. The first file (OUT) summarized model results for each run. It listed growing season precipitation, starting soil moisture on April 9 (SSM), CU, yields (of both the first and second cuts of alfalfa), the number of irrigations, the total net irrigation amount, the variable costs associated with irrigation, and the net return each year. This file also contained the mean and standard deviation of soil moisture on October 15, total ET during the simulation season, CU, yields, seasonal net irrigation application, irrigation labour for the entire irrigated area, total irrigation costs, and net returns. The second output file (OYR) contained more detailed data for each year. This included the dates growth started and finished, total precipitation during the simulation season, the date each irrigation was started and the irrigation amount (and the field which was irrigated if a TCP), soil moisture on October 15, accumulated deep percolation, and total surface runoff. In addition to the above data, the option existed to output the following daily estimates in file OYR: precipitation, PET, soil moisture, ET, accumulated yield, irrigated area, and net irrigation depth. Appendix C contains examples of program output.

4.1 Weather

The lengths of wet and dry spells for the historical record and for 50 years of simulated weather were compared for five periods: April 9 to May 16, May 17 to June 23, June 24 to July 31, August 1 to September 7, and September 8 to October 15. Wet and dry spells which spanned the boundaries of these periods were assigned to the period in which the spell ended. A spell which contained a day with unknown precipitation was ignored. A chi-squared test was performed to test if the lengths of wet and dry spells were independent of whether the weather was real or artificially generated. With the exception of wet spells from August 1 to September 7 at Coronation, all were found to be independent at the 95% level of confidence. For the above period at Coronation, the simulated data underestimated the length of wet spells.

The average precipitation totals for each ten day period for historical data and for simulated weather generated from the combination of simple Markov chain and cube root normal distribution were compared. Figures 4.1, 4.2, and 4.3 plot the ten day average precipitation totals for Coronation, Edmonton, and Lacombe. A t-test showed the average totals were the same as historical totals at a 90% level of confidence. There was a trend, however, for the simulated averages to be slightly less than those observed historically. This difference can likely be attributed to

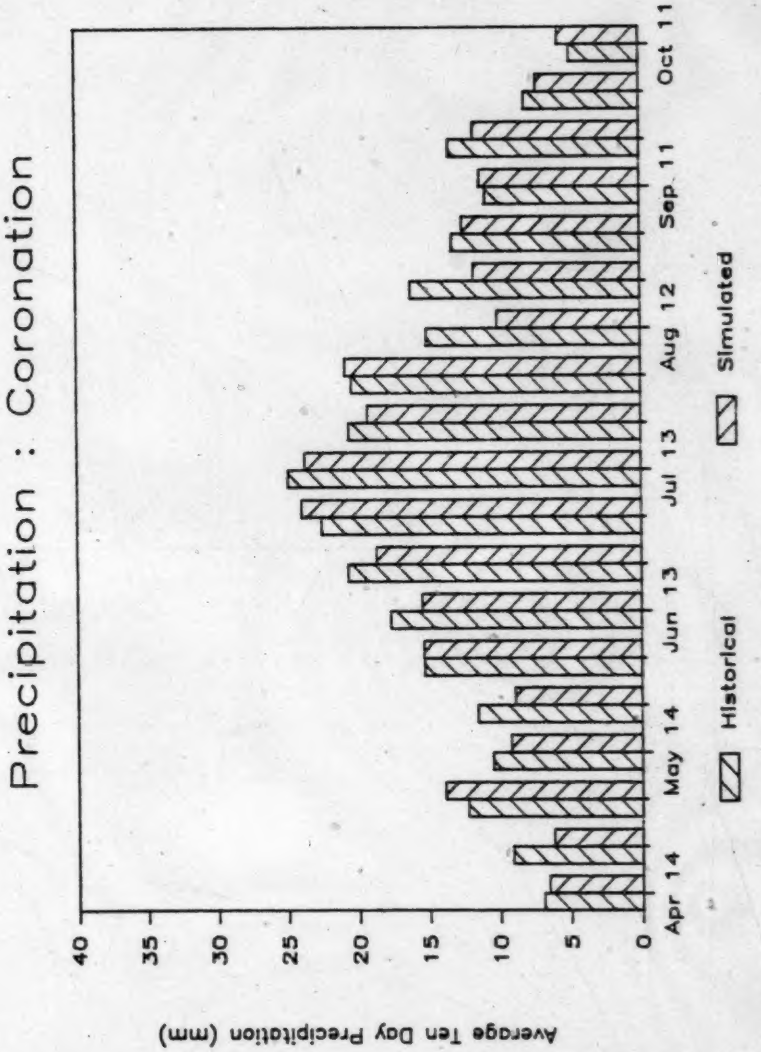


Figure 4.1 Historical and Simulated Ten Day Precipitation Totals at Coronation

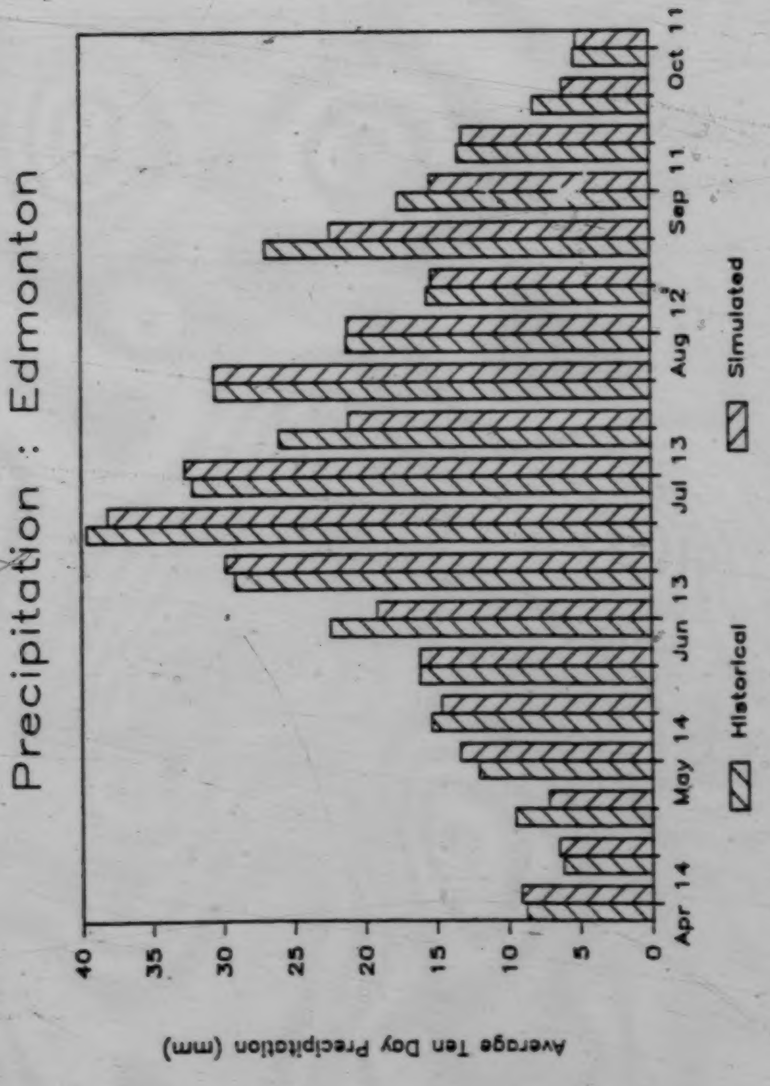


Figure 4.2 Historical and Simulated Ten Day Precipitation Totals at Edmonton

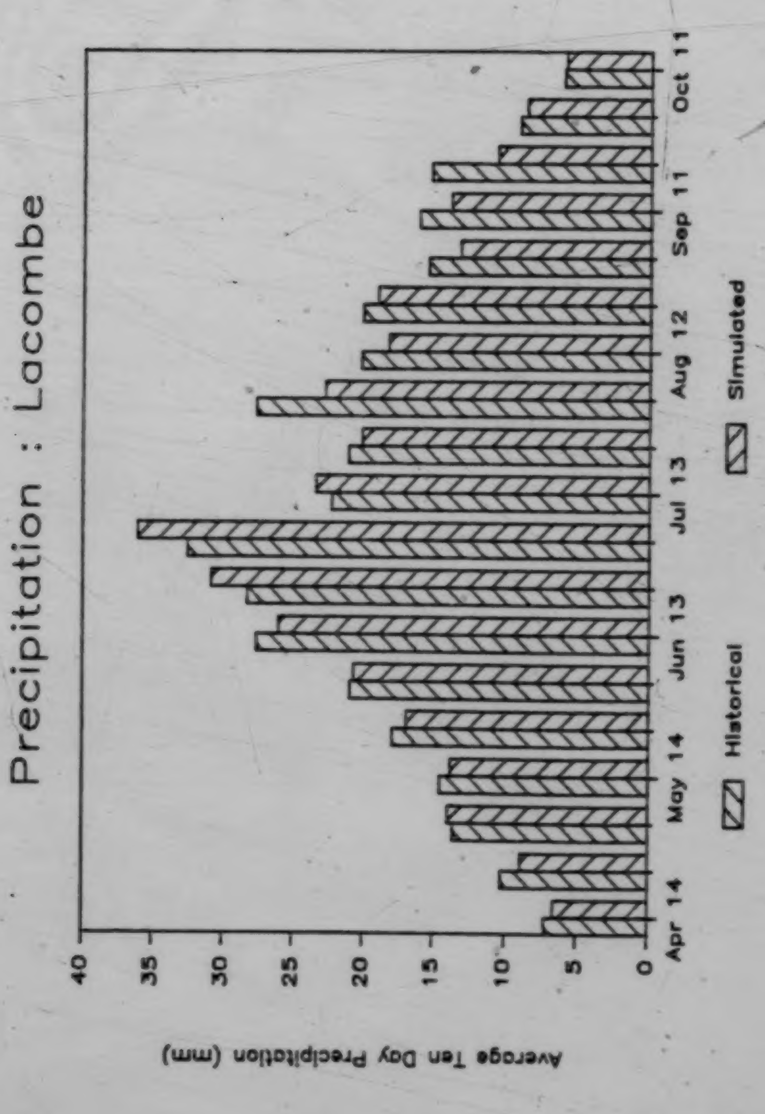


Figure 4.3 Historical and Simulated Ten Day Precipitation Totals at Lacombe

very heavy precipitation events (> 40 mm/d). Based on the cube root normal distribution the upper extreme of precipitation appeared to be smaller than those which have been actually recorded. Although these heavy rains happen infrequently, the quantity of precipitation involved is sufficient to raise the mean for the historical data. From the point of view of modeling soil moisture, omitting generation of these heavy rains is not crucial since much of this rain would probably be lost as surface runoff and/or deep percolation below the root zone.

The weather model generated a wide range of growing season precipitations at all locations. Table 4.1 lists the generated growing season average precipitation, and the range and standard deviation of generated growing season average precipitation based on 25 seasons.

Table 4.1 Average and Variation of Generated Precipitation During the Growing Season

	Growing Season Precipitation (mm)					
	Alfalfa			Wheat		
Location	mean	SD	range	mean	SD	range
Cor.	225	39	131 - 317	162	37	82 - 248
Edm.	294	68	155 - 495	246	58	132 - 436
Lac.	280	53	162 - 434	241	46	117 - 425
Leth.	230	54	139 - 392	168	49	75 - 264

Since the simple Markov chain applies to central and southern Alberta, it is comparatively simple to determine the probability of having a spell of wet or dry days of specified length. The probability of having a dry spell of n days, if the first day is dry is (Simpson and Henry 1966):

$$(1-P(W/D))^{n-1} \qquad (4.1)$$

Figures 4.4 plots the probabilities of having n dry days at Coronation, Edmonton, Lacombe, and Lethbridge for the period from May 9 to 18. Figures 4.5, 4.6 and 4.7 are similar but for June 28 to July 7, July 28 to August 6, and August 27 to September 5, respectively.

The average length of a dry spell is:

$$1/(P(W/D)) \qquad (4.2)$$

The absolute probability of having a dry day is:

$$P(D) = 1- P(W/D)/[P(W/D)+(1-P(W/W))] \qquad (4.3)$$

The absolute probability of having a wet day is:

$$P(W) = 1- P(D) \qquad (4.4)$$

The mean number of dry days during n days is:

$$m(D) = P(D) * n \qquad (4.5)$$

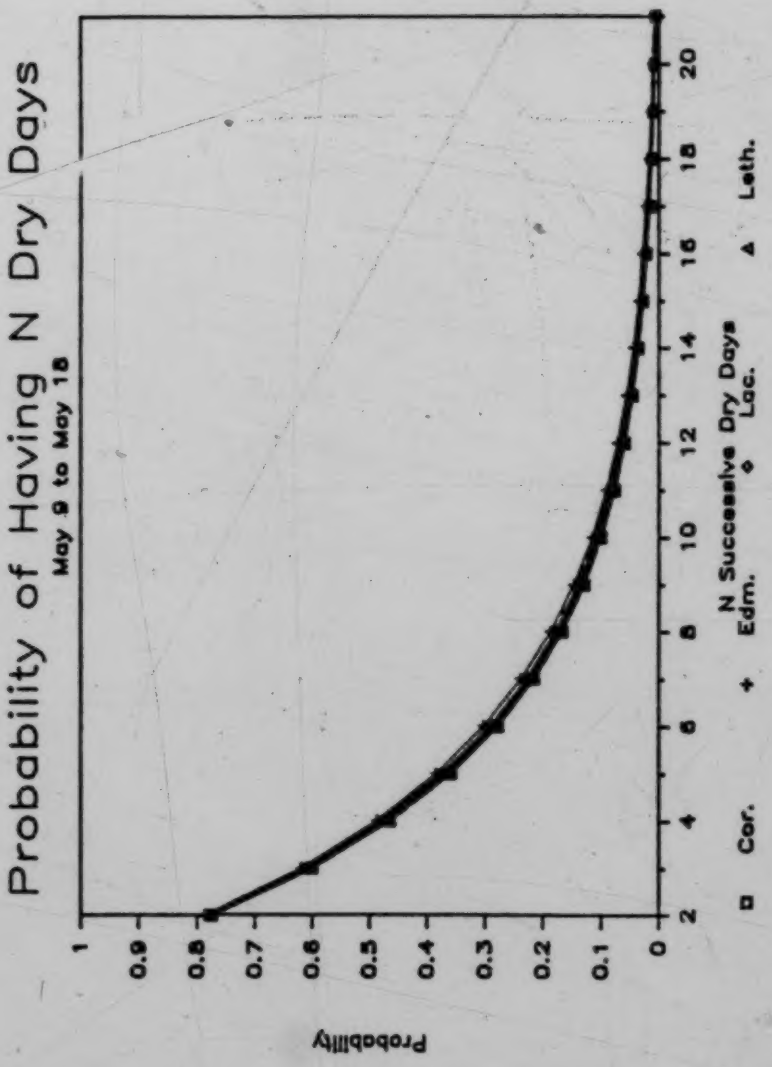


Figure 4.4 Probability of Having N Dry Days at Coronation, Edmonton, Lacombe and Lethbridge from May 9 to 18

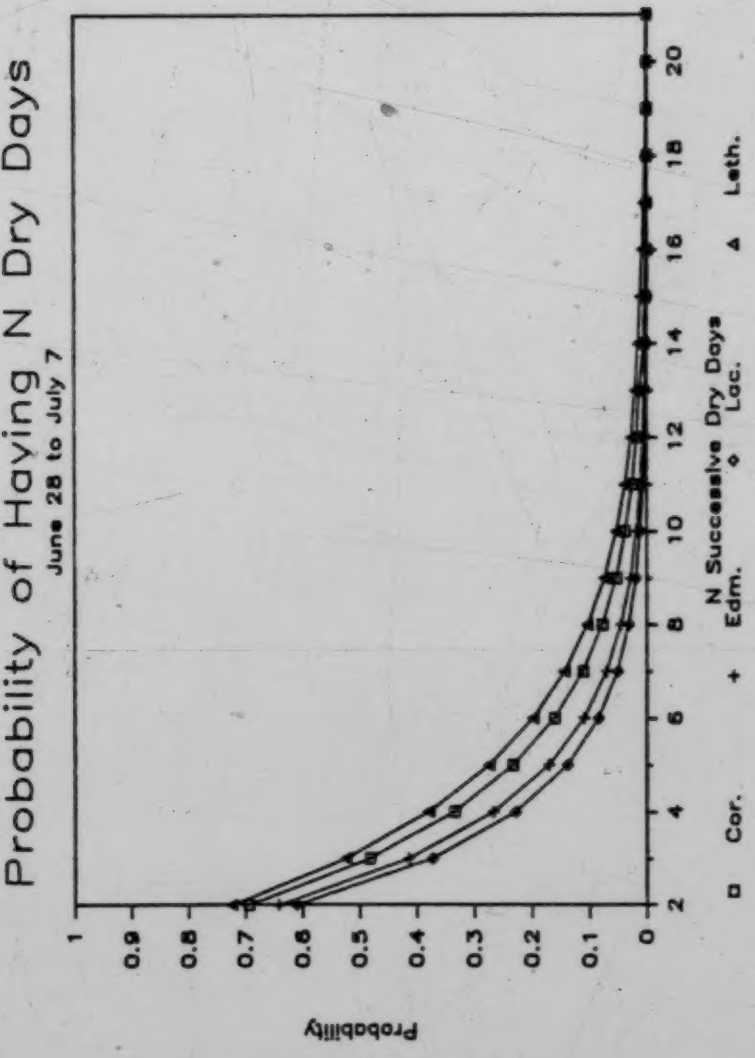


Figure 4.5 Probability of Having N Dry Days at Coronation, Edmonton, Lacombe, and Lethbridge from June 28 to July 7

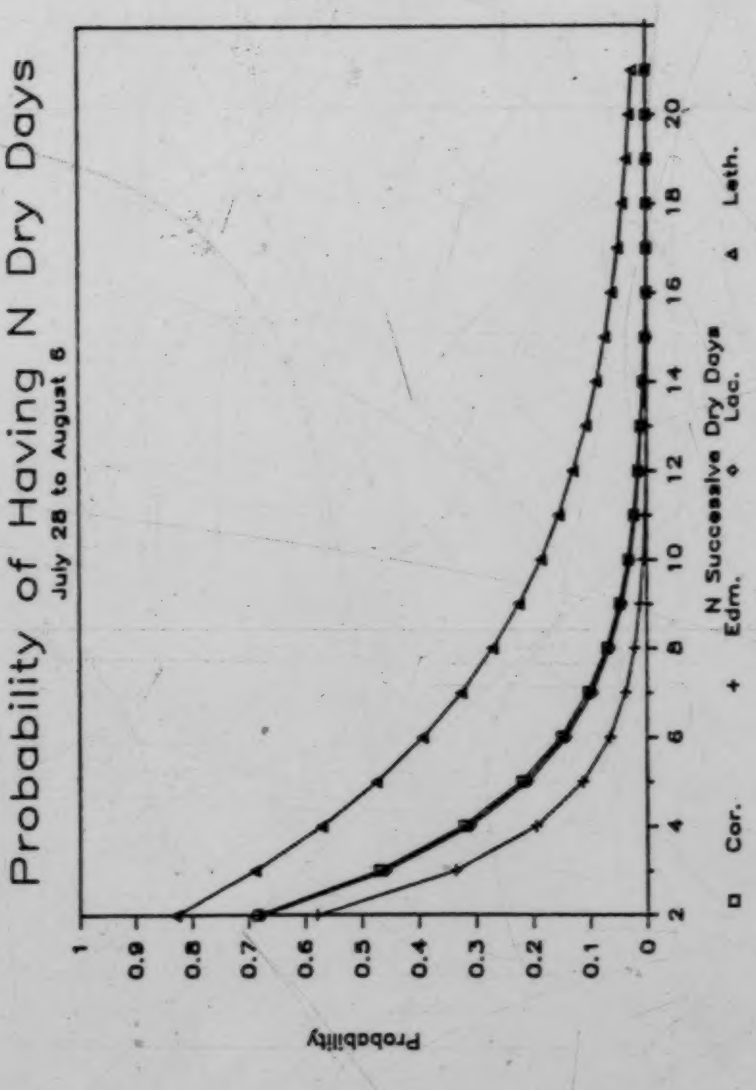


Figure 4.6 Probability of Having N Dry Days at Coronation, Edmonton, Lacombe, and Lethbridge from July 28 to August 6

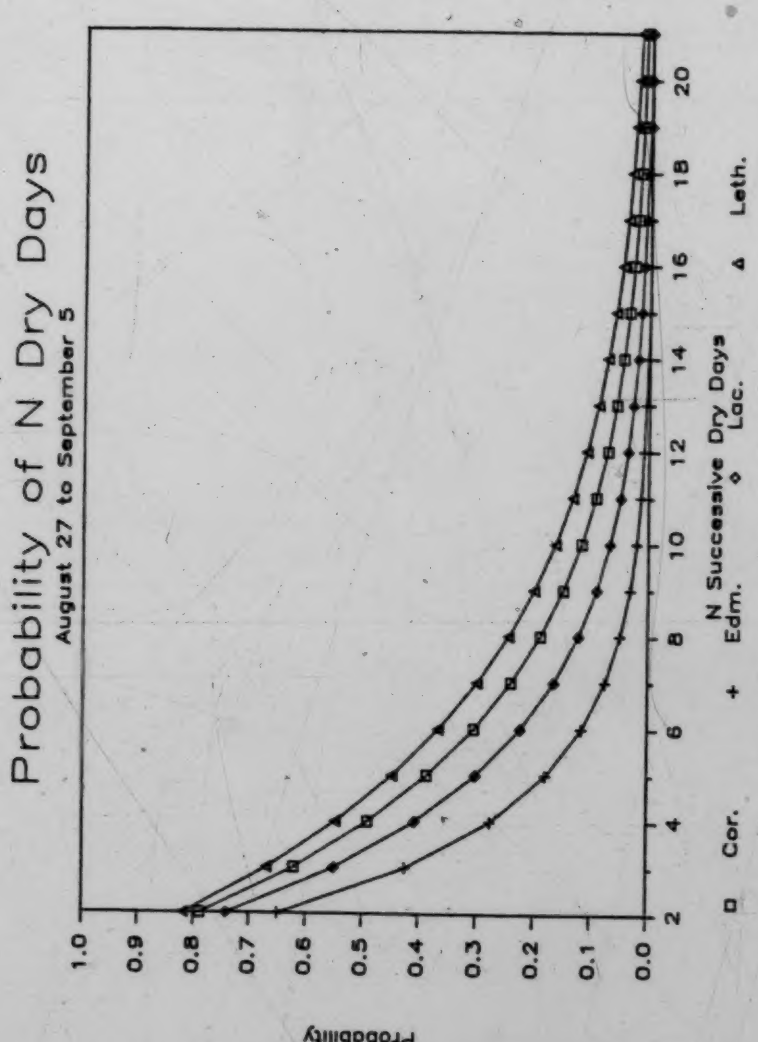


Figure 4.7 Probability of Having N Dry Days at Coronation, Edmonton, Lacombe, and Lethbridge from August 27 to September 5

Table 4.2 gives the average length of dry spell and absolute probability of having a dry day during each ten day period for Coronation, Edmonton, Lacombe, and Lethbridge.

Intermittent move irrigation systems have an irrigation interval -- the time required for the system to complete an entire irrigation of the field. From Figures 4.4 to 4.7, it is apparent that dry spells longer than ten days are rare at any of the east central Alberta locations. In east central Alberta, providing the irrigation interval is greater than ten days, there will likely be some rain during an irrigation. At Lethbridge, however, by mid summer, dry spells of ten days or more are not exceptional. Therefore, an irrigation system at Lethbridge should be sized so that potential crop moisture needs are met during a dry period lasting the entire irrigation interval. Appendix D lists the Markov transitional probabilities and the mean and standard deviations of the cube root of precipitation on wet days resulting from the weather analysis.

Mean total PET for each ten day period based on 50 years of simulated weather were compared with means calculated from historical records for Coronation, Edmonton, and Lacombe. A t-test showed that the simulated and historical ten day PET means were consistently the same at the 95% level of confidence. However, the variance of the simulated means was always less than that observed

Table 4.2 Average Length of Dry Spells and the Probability of a Dry Day Occurring From April 9 to October 15 for Coronation, Edmonton, Lacombe, and Lethbridge

	Coronation		Edmonton		Lacombe		Lethbridge	
Period	Dry Spell (d)	P(D)	Dry Spell (d)	P(D)	Dry Spell (d)	P(D)	Dry Spell (d)	P(D)
Apr 9-Apr 18	4.9	0.780	4.7	0.745	5.2	0.777	6.3	0.777
Apr 19-Apr 28	5.6	0.735	6.3	0.776	5.7	0.758	4.7	0.706
Apr 29-May 8	6.1	0.762	5.5	0.746	5.3	0.753	4.3	0.714
May 9-May 18	4.4	0.719	4.7	0.719	4.6	0.691	4.5	0.700
May 19-May 28	4.7	0.726	4.2	0.676	3.3	0.663	4.2	0.692
May 29-Jun 7	3.8	0.657	4.0	0.687	3.2	0.620	3.3	0.586
Jun 8-Jun 17	3.3	0.638	2.6	0.560	2.9	0.565	3.7	0.639
Jun 18-Jun 27	3.3	0.595	3.0	0.566	2.7	0.553	3.6	0.643
Jun 28-Jul 7	3.3	0.607	2.8	0.549	2.6	0.522	3.6	0.673
Jul 8-Jul 17	3.5	0.645	2.5	0.567	3.0	0.615	5.0	0.735
Jul 18-Jul 27	3.3	0.661	2.7	0.556	3.2	0.623	7.0	0.807
Jul 28-Aug 6	3.2	0.633	2.4	0.534	3.1	0.588	5.9	0.769
Aug 7-Aug 16	4.2	0.744	3.2	0.618	3.6	0.662	5.7	0.793
Aug 17-Aug 26	4.9	0.715	3.8	0.652	3.7	0.664	5.6	0.771
Aug 27-Sep 5	4.7	0.725	2.9	0.586	3.9	0.683	5.5	0.768
Sep 6-Sep 15	5.5	0.739	3.7	0.645	4.3	0.690	5.1	0.752
Sep 16-Sep 25	5.9	0.751	4.3	0.688	4.2	0.678	5.4	0.727
Sep 26-Oct 5	5.6	0.784	5.2	0.755	5.4	0.752	6.6	0.785
Oct 6-Oct 15	8.3	0.831	7.1	0.815	6.3	0.814	6.5	0.812

historically. This strongly suggested there were periods of weather with above or below normal PET beyond those explained by wet and dry spells. The weather model assumed that each day was independent with respect to temperatures and PET. Hence these trends would not be preserved. The historical ten day total of PET would have a larger range of values than the simulated, giving the historical totals a larger variance.

The weather model, therefore, underestimated the variation in irrigation requirements and crop yields (as affected by PET) during each ten day period. Provided that trends of below or above normal PET do not persist for much longer than ten days, the effect on seasonal irrigation requirements and seasonal yields is probably not great.

Richardson (1979) developed a method of computer generation of daily maximum and minimum temperatures, and solar insolation. The simulation technique includes the serial (i.e. between days) correlation among the three variables. This model also incorporates the cross correlations among these weather variables. Therefore, this approach would probably better preserve trends of above and below normal temperatures (which would produce trends of above and below normal PET). However, a great deal of processing is required to analyze historical weather records to estimate the parameters needed to generate the weather variables.

Appendix E tabulates the temperature and PET statistics used to generate temperatures and PET. Appendix F gives the mean and standard deviation of daily PET resulting from the weather analysis.

4.2 Crop Growth and Consumptive Use Models

Validation of the crop growth model and consumptive use model was difficult because there have been very few irrigation trials conducted in east central Alberta. Most research on crop yield response to moisture conditions on the Prairies has been conducted in southern Alberta or southwestern Saskatchewan. Unfortunately, there exists significant climatic differences between these areas and east central Alberta. The problem of validating the model was compounded by the variation in crop yields and moisture use for the same area between different experiments.

The crop growth and consumptive use models had to be calibrated. Because of the complexity of the model, most of the calibration was accomplished through trial and error. The danger of calibrating the model to crop yield and moisture use data from one experiment is that the model may only become applicable to the climate specific to the years of the experiment, for the soil on which the experiment was conducted, and for the type of crop management used.

Considering the above, the approach used to calibrate and validate the model was to have the model agree reasonably well with a wide variety of data available in the literature but not necessarily agree very well with any one data set. This is consistent with the objectives of the study which was to construct a computer model which would be suitable for a wide geographical area, applicable on a variety of soils, and representative of results expected on farms.

Three-quarters on the effort expended to develop and implement the model was devoted to the yield simulation component. It is probably impossible to devise a simple yield model which will accurately simulate plant growth except, maybe, for a specific site, soil, and type of crop management. This is especially true when one is trying to predict seed yield alone. Because the yield models are gross simplifications, the variation in seasonal yields was less than that found in reality. Consequently, the yield models best capture trends in crop yield response to moisture conditions rather than providing a good prediction of crop yield in any one specific year.

In general, the choice of modeling on a daily basis was a good one. First, simulatioinon a daily basis produced a better representation of the real world. Crop growth was dependent on the timing of precipitation and not only on the total amount of precipitation which fell during the growing season. Simulating on a daily basis created some very real irrigation problems -- substantial rains falling soon after irrigation had started and unusual extended periods of hot, dry weather during which the irrigator could not keep up with crop water demand. The decision to model the area irrigated with a side roll and HHT separately in three parts was appropriate. Frequently there were significant differences in moisture conditions across the irrigated area.

Stewart (1981) stated that farm yields in Canada of most common crops are inevitably at least 15% less than potential yields because of losses due to weeds, diseases, and pests. This suggests the value of the management factor, M, should be about 0.85. Setting M to 0.75 was found to predict yields which were in good agreement with expected farm yields. Typically, setting M to 0.85 produced yields more representative of the top producing farmers while setting M to 1.0 gave yields only expected on extremely well managed research plots.

One of the most important sources of data with which to validate the model was published irrigation trials. Validating predicted crop CU is difficult because the starting and ending dates of irrigation are rarely given in the methodology of published experiments. Also, the dates between which CU is measured are often not specified. By contrast, the predicted crop CU was measured between very specific dates -- start of growth and end of growth (although, for alfalfa, these dates would be difficult to determine in practice). Predicted total CU refers to total ET during the entire simulation period -- April 9 to October 15.

Validation of the model was also complicated by the fact that few irrigation trials have been conducted for more than four years. Because of the weather variability, four years may not necessarily be representative of the weather over the lifetime of the irrigation system. Successive years from the predicted results for the number of years of the actual crop yield trials could usually be chosen which provided excellent agreement between measured and predicted. On the other hand, successive periods from the model results could be selected which had very poor agreement with measured results. The approach used was to compare measured crop yield and CU with predicted performance for a 25 simulated years. For this reason, perfect agreement with measured yields and CU was practically impossible.

Predicted yields were also validated by comparing them to typical or average farm yields. This was a valuable approach to validate the model because it takes into account normal effect of weather and management. Using typical farm yields also helped ensure the model had general applicability for a large area.

4.2.1 Alfalfa Development

Tables 4.3 through 4.6 show the predicted dates alfalfa reaches distinct crop development stages at Coronation, Edmonton, Lacombe, and Lethbridge, respectively. These dates were from ten year model runs.

Hobbs and Krogman (1966) recorded the time required for alfalfa to reach specific development stages in southern Alberta over a three year period. Table 4.7 gives the average measured time spans along with those predicted at Lethbridge. In general there was good agreement between predicted and measured development rates. However, the total growing period for alfalfa was overestimated by the model. The growing periods for the other locations also appear to be longer than would be expected. The probable cause was that the start of effective growth was estimated to start too early. If growth commenced about a week later than predicted, then the growing season length would be more appropriate. At the east central Alberta locations, delaying the start of growth would mean that two complete growths would not occur in all years. This suggests that less than 500 degree days were required for alfalfa to reach the cutting stage.

Since seasonal yield is the sum of daily growth, reducing the number of days within each growth would correspondingly reduce yield. The effect would be minimal in east central Alberta. Providing start of growth in the

Table 4.3 Predicted Alfalfa Development Rates at Coronation

Growth Stage	Range	Mean
Start of Growth	Apr 28 - May 10	May 3
Full Cover	June 8 - June 16	June 10
First Cut	July 3 - July 8	July 5
Full Cover	July 23 - July 28	July 26
Second Cut	Aug 12 - Aug 23	Aug 17
End of Growth	Aug 29 - Oct 7	Sept 17
Growing Season Length (d)	114 - 150	138

Table 4.4 Predicted Alfalfa Development Rates at Edmonton

Growth Stage	Range	Mean
Start of Growth	Apr 30 - May 13	May 4
Full Cover	June 7 - June 14	June 11
First Cut	July 4 - July 11	July 7
Full Cover	July 28 - Aug 3	July 31
Second Cut	Aug 18 - Aug 28	Aug 24
End of Growth	Sept 8 - Oct 1	Sept 30
Growing Season Length (d)	132 - 150	142

Table 4.5 Predicted Alfalfa Development Rates at Lacombe

Growth Stage	Range	Mean
Start of Growth	Apr 30 - May 10	May 3
Full Cover	June 9 - June 16	June 13
First Cut	July 5 - July 15	July 10
Full Cover	July 20 - Aug 8	July 31
Second Cut	Aug 19 - Sept 1	Aug 24
End of Growth	Aug 17 - Sept 27	Sept 11
Growing Season Length (d)	105 - 152	135

Table 4.6 Predicted Alfalfa Development Rates at Lethbridge

Growth Stage	Range	Mean
Start of Growth	Apr 18 - May 5	Apr 26
Full Cover	June 1 - June 12	June 4
First Cut	June 24 - July 12	June 28
Full Cover	July 15 - July 21	July 17
Second Cut	Aug 1 - Aug 9	Aug 4
End of Growth	Aug 28 - Oct 6	Sept 21
Growing Season Length (d)	134 - 163	146

Table 4.7 Comparison of Predicted Alfalfa Growth Rates at Lethbridge with Measured Alfalfa Growth Rates in Hobbs and Krogman (1966)

Growth Stage	measured	predicted
start of growth to full cover (d)	36	39
full cover to first cut (d)	24	24
first cut of full cover (d)	11	18
full cover to second cut (d)	21	18
second cut to end of growth (d)	46	47
	138	146

spring is delayed, the main effect of decreasing the number of degree days to reach the cutting stage would be to eliminate the growing days at the beginning of the first growth and the last growing days during the second growth. Because the temperatures and photosynthetic fluxes are smaller on these days, the effect on yield would likely be small. At Lethbridge, however, decreasing the number of degree days needed to reach the cutting stage would reduce seasonal dryland yield significantly. Here the second dryland growth was predicted to be below the minimum of 1100 kg/ha about one year out of two. When a second cut was taken, it was normally not much more than the minimum of 1100 kg/ha. Therefore, any reduction of the yield of the second cut would have a substantial effect on seasonal dryland yields. The impact on irrigated yields at Lethbridge would not be as great.

The model predicted a third cut was possible most years at Lethbridge. Normally the crop was projected to reach the cutting stage about the same time it was killed by a hard fall frost. From a agronomic perspective, this third harvest should be taken after the frost to ensure the stand has stored sufficient root reserves. In comparison with southern Alberta, the model predicted a third cut was rarely possible at any of the east central Alberta locations, especially at Lacombe.

4.2.2 Wheat Development

Tables 4.8 to 4.11 give the predicted dates wheat reaches specific crop development stages at Coronation, Edmonton, Lacombe, and Lethbridge, respectively. Robertson (1968) listed the average dates for five crop years of wheat at Lacombe -- planting: May 16; emergence: May 26; jointing: June 10; heading: July 12; soft dough: August 15; ripe: September 3. Therefore the predicted dates for Lacombe were reasonable estimates of actual dates.

The planting dates are earlier than all wheat would be expected to be seeded on farms. The effect of delaying seeding less than ten days on yields and CU would probably be marginal.

Table 4.8 Predicted Wheat Development Dates at Coronation

Growth Stage	Range	Mean
Seeding	May 8 - May 22	May 14
Emergence	May 18 - May 31	May 24
Jointing	June 10 - June 21	June 15
Heading	July 7 - July 18	July 12
Soft Dough	July 31 - Aug 13	Aug 7
Ripe	Aug 14 - Aug 30	Aug 21
Growing Season Length (d)	93 - 104	99

Table 4.9 Predicted Wheat Development Dates at Edmonton

Growth Stage	Range	Mean
Seeding	May 12 - May 17	May 13
Emergence	May 20 - May 26	May 23
Jointing	June 12 - June 18	June 14
Heading	July 11 - July 16	July 14
Soft Dough	Aug 8 - Aug 15	Aug 11
Ripe	Aug 23 - Sept 4	Aug 28
Growing Season Length (d)	102 - 112	108

Table 4.10 Predicted Wheat Development Dates at Lacombe

Growth Stage	Range	Mean
Seeding	May 8 - May 27	May 15
Emergence	May 19 - June 5	May 24
Jointing	June 13 - June 26	June 17
Heading	July 13 - July 23	July 16
Soft Dough	Aug 7 - Aug 16	Aug 12
Ripe	Aug 26 - Sept 20	Sept 2
Growing Season Length (d)	103 - 118	110

Table 4.11 Predicted Wheat Development Dates at Lethbridge

Growth Stage	Range	Mean
Seeding	May 3 - May 18	May 9
Emergence	May 13 - May 27	May 19
Jointing	June 8 - June 17	June 12
Heading	July 4 - July 15	July 7
Soft Dough	July 24 - Aug 5	July 30
Ripe	Aug 6 - Aug 17	Aug 11
Growing Season Length (d)	87 - 100	94

Lacombe and Lethbridge had the most variation in development dates because those sites had the greatest likelihood of having wet seeding weather. The variation in seeding dates was carried forward into the remainder of the growing season. The crops matured more rapidly at Coronation and Lethbridge because these locations tend to have the hottest summer weather of all the study sites.

Of all the locations, Lacombe had the most chance of frost during the wheat growing season. In addition, Lacombe also had the most chance of having delayed seeding because of cool, damp weather. Finally, wheat development was most delayed at Lacombe because the weather tended to be slightly cooler during the summer. For these three reasons, Lacombe was predicted to have the most damage due to frost (especially early fall frosts) of all the locations considered. Total loss was predicted to occur about one out of every ten years at Lacombe. Frost damage during the period from the hard dough stage to swathing was predicted to occur a further one out of ten years (in the model results, this was indicated by unexpectedly low WUE for the irrigated crop). Frost damage was not predicted to be a concern at Coronation or Lethbridge, and only happened about one out of 25 years at Edmonton. Peters et al. (1978) noted that less than 5% of the land area in the Lacombe district is seeded to wheat in any one year because of the hazard of frosts.

4.2.3 Discussion of the Simulation of Alfalfa Yield and Moisture Use

Validation of simulated alfalfa yields for southern Alberta was complicated because either two or three alfalfa harvests per year are possible. Rarely was the number of cuts taken given in published alfalfa yield trials in southern Alberta.

Unless otherwise stated, irrigation of alfalfa in the model was not started until June 1 or continued after a few days prior to the second cutting of alfalfa. Also, unless specified, the management factor, M, was set at 0.75.

Where published yields were on a dry matter basis, these are presented in this study at a 15% moisture content. Similarly, all model results refer to yield at 15% moisture content.

Hobbs et al. (1963) measured yields and consumptive use in southern Alberta for two and three year old alfalfa stands for a period of three years. The results of this experiment and predicted model results are presented in Table 4.12. The model results are for a stationary centre pivot (SCP) at Lethbridge. Generally the model provided good estimates of alfalfa yields and CU.

Table 4.12 Comparison of Alfalfa Yields and CU in Hobbs et al. (1963) with Predicted Yields and CU

	Measured		Predicted	
	range	mean	range	mean
75% AM depletion				
Yield (kg/ha)	6481 - 13491	9302	7788 - 10482	9160
CU (mm)	328 - 696	504	466 - 618	543
50% AM depletion				
Yield (kg/ha)	7777 - 15739	11542	9611 - 11414	10442
CU (mm)	457 - 752	617	506 - 679	607
25% AM depletion				
Yield (kg/ha)	9231 - 16241	11921	11137 - 13580	12184
CU (mm)	513 - 879	691	603 - 760	693

Comparison of the measured alfalfa yields and CU with predicted results revealed an important characteristic of the model -- the predicted variation in yields and CU were invariably less than those experienced in actual crop trials. There are three likely explanations for this behavior (in expected order of importance): i) the modified Wageningen model does not account for all factors which affect yield, ii) predicted variation in PET during any period was less than the real world which reduced variation in both CU and yield, and iii) the VSMB did not include all the influences on plant moisture consumption and soil moisture movement.

If irrigation was carried on following the second cut then the predicted CU was overestimated compared with the CU measured by Hobbs et al. (1963). Allowing irrigation until September would increase the predicted CU. With a SCP irrigating at 50% AM depletion CU becomes 739 mm (range: 671 - 835). This possible overestimation of ET was not as pronounced with other irrigation systems. A side roll (16 ha/lateral) also irrigating at 50% AM depletion until September produced a predicted average CU of 677 mm. When irrigating only until the second cut with the latter system the estimated CU was essentially the same as the SCP -- 600 mm. The assumed k coefficients may be too large during the third growth, especially during the period immediately following the second cut. Scott (1975) used actual experimental data to derive a set of k coefficients for Lethbridge. His k coefficients were considerably less during the third growth ~~than those~~ used in the model. The choice of k coefficients for the third growth is less important in east central Alberta because proportionately less CU takes place during that growth stage.

The model may overestimate the yield increase from reducing AM depletion to less than 50%. Both Hobbs et al. (1963) and Bezeau and Sonmor (1964) concluded there is little advantage to maintaining the AM of an irrigated soil less than 50% depleted. An examination of the yield model indicates that any practice which increases ET will increase yield. Therefore, when the irrigation system was set to irrigate at less than 50% AM depletion, both CU and yield increased. In reality there should probably be some sort of extravagance factor which would cause WUE to decrease as CU approaches potential CU. It is important to note that the predicted alfalfa yields only show a large response to maintaining AM less than 50% depleted when irrigated with a SCP. The predicted response was less dramatic when irrigation was accomplished with any other irrigation system.

Korven and Wiens (1974) compared the effect of varying the irrigation interval of a side roll at Swift Current. PET at Swift Current is similar to that at Lethbridge. This experiment was conducted for four years with irrigation intervals of 14, 21, and 28 days. The 14 day interval represents a system with can almost always supply crop water needs even during hot, dry spells. Irrigation was started when the AM in the soil became about 50% depleted. Table 4.13 summarizes the experimental results and also lists the predicted results at Lethbridge with the same irrigation intervals with a side roll irrigating at 50% AM depletion.

The model provided very good agreement with the experimental results if the M was raised to 0.81. This indicates the real crop was managed better than assumed. As well, there was good agreement between the actual and predicted yields for the first and second cuts. It is not valid to compare dryland yields at Lethbridge and Swift Current because of differences between amount and timing of precipitation. However, the dryland yields did conform to each other. In two years the second cut at Swift Current

Table 4.13 Comparison of Alfalfa Yields and CU in Korven and Wiens (1974) with Predicted Yields and CU

	Measured		Predicted		
	range	mean	range	mean M=.75	mean M=.81
14 day irrigation interval					
cut 1 kg/ha	4297- 6839	5121	3472- 6427	4965	5362
cut 2 kg/ha	3746- 4801	4297	3590- 4620	4100	4428
total kg/ha	8395-10824	9418	8195-10844	9065	9790
CU mm	480- 650	565	468- 659	562	--
21 day irrigation interval					
cut 1 kg/ha	3964- 6048	4608	3002- 5523	4290	4633
cut 2 kg/ha	2373- 4505	3487	2599- 3928	3294	3558
total kg/ha	7638- 8680	8095	6390- 9288	7584	8191
CU mm	400- 540	465	412- 609	488	--
28 day irrigaion interval					
cut 1 kg/ha	3369- 4537	4114	2525- 4929	3879	4189
cut 2 kg/ha	1779- 4156	3120	2178- 3111	2723	2941
total kg/ha	6190- 8245	7234	5122- 7845	6603	7130
CU mm	410- 480	443	342- 553	427	--
dryland					
cut 1 kg/ha	1689- 3928	2626	1455- 4419	2899	3131
cut 2 kg/ha	587- 2658	1515	0- 1700	662	715
total kg/ha	2276- 5840	4141	1455- 5930	3561	3846
CU mm	140- 390	230	195- 372	283	--

was less than 1100 kg/ha. In the simulation these cuts would not have been taken. Eliminating these small cuts would reduce the actual average dryland yield to 3769 kg/ha which is very close to the predicted average dryland yield at Lethbridge with M equal to 0.81.

Korven and Kilcher (1979) present the results of irrigated alfalfa yield trials at Swift Current. The yield trials were carried on for six years with the purpose of comparing the effects of varying the period of irrigation. One of the treatments involved irrigating from late spring to early fall and another involved irrigating from early May until the first cut. These irrigation treatments were simulated for Lethbridge using a side roll irrigating at 50% AM depletion (which was similar to the irrigation method used in the experiment). The experimental and predicted results are shown in Table 4.14. These results indicate the model may be overestimating the first cut and underestimating the second cut yields. However, the predicted seasonal yields were withing 5% of the measured.

Pohjakas (1981) studied irrigation practices with centre pivots on farms in southern Alberta for four years. The mean alfalfa yield was 9463 kg/ha. He noted that farmers were not irrigating to potential crop demand. A model run allowing 75% AM depletion with a SCP produced average alfalfa yields of 9160 kg/ha which is within 5% of the average yields found by Pohjakas.

Table 4.14 Comparison of Alfalfa Yields in Korven and Kilcher (1979) with Predicted Yields (kg/ha)

	Measured		Predicted		
	range	mean	range	mean M=.75	mean M=.78
late spring to early fall					
cut 1	3378- 5376	4583	3474- 6427	4965	5173
cut 2	3876- 5971	4949	3590- 4460	4100	4271
total	7254-11168	9532	7607-10844	9065	9444
early spring to first cut					
cut 1	3952- 5352	4652	4828- 6843	5638	5874
cut 2	1188- 4829	3578	1667- 3882	2346	2444
total	5104-10182	8231	6658-10725	7985	8318

Sonmor (1963) analyzed the results of 12 years of various irrigation trials in southern Alberta. He found the best alfalfa yields were in the order of 11700 kg/ha with a corresponding CU of 648 mm. Pittman (1973) states that, with above average management, average alfalfa yields on irrigated farms in southern Alberta are about 11200 kg/ha. With well managed irrigation, the CU of alfalfa in southern Alberta is about 600 mm (Alberta Agriculture 1982) to 660 mm (Korven and Randall 1975). Irrigating with a stationary centre pivot at 50% AM depletion at Lethbridge, the predicted average yield was 10444 kg/ha with CU of 607 mm and irrigating at 35% AM depletion the predicted average yield was 11804 kg/ha with a CU of 661 mm. These predicted yields and CU were satisfactory estimates of expected CU and yield in southern Alberta.

During the 1950's and early 1960's, a number of irrigated crop yield trials were conducted for the, as yet, undeveloped William Pearse Irrigation Project (Toogood 1963). This potential irrigation development is also called the Red Deer River Irrigation Project. The experiments were conducted on Solonetzic soils about 80 km south of Coronation. Among these experiments, two years of consumptive use and yield trials were carried out for fertilized alfalfa using several levels of allowable AM depletion. Table 4.15 lists the measured alfalfa yield and CU along with the predicted model results on soil type II at Coronation irrigating with a SCP. The measured alfalfa yields were considerably lower than the predicted results. Also the alfalfa in the experiment was more responsive to reductions in allowable AM depletion than the model estimated. However, the soil at the experiment site had a much shallower root zone than soil type II. Because of its lower moisture storage capacity, the shallower root zone would impart greater yield sensitivity to allowable AM depletion than would soil type II. Toogood noted that soil properties at the experiment site varied greatly between individual plots. As a result, there was an unexpectedly large yield variation between replicates. For this reason, it is difficult to make comparisons to the 25 year model results with the two

Table 4.15 Comparison of Alfalfa Yields and CU in Toogood (1963) with Predicted Yields and CU

	measured		predicted		
	range	mean	range	mean M=.75	mean M=.38
dryland					
yield kg/ha	476- 926	701	1813- 5196	3746	1895
CU mm	211- 376	294	168- 327	250	--
75% AM depletion					
yield kg/ha	1958- 2487	2223	7090- 8160	7642	3866
CU mm	348- 472	410	345- 451	408	--
50% AM depletion					
yield kg/ha	3175- 6058	4974	8027- 9472	8683	4393
CU mm	356- 495	451	374- 505	449	--
35% AM depletion					
yield kg/ha	7011- 7037	7024	8672- 10145	9422	4767
CU mm	483- 521	502	388- 530	479	--

year experimental results. The predicted alfalfa CU agreed well with the measured values.

Allen and Elgaard (1963) surveyed farm yields in all irrigation districts in southern Alberta during 1963. In the Lethbridge Northern Irrigation District (which lies immediately north of Lethbridge) average dryland alfalfa yields were 2242 kg/ha compared with 6950 kg/ha for irrigated alfalfa. This was an approximate tripling of alfalfa yield with irrigation -- a proportionate increase estimated by the model. These surveyed yields suggest that the appropriate management factor during 1963 was about

0.57 rather the assumed 0.75. This implies the alfalfa stands were not as well managed as assumed in the simulation.

The South Saskatchewan River Irrigation District in central Saskatchewan lies 350 km east of Coronation and has a climate similar to Coronation. Linsley and Hamlin (1984) reported that mean irrigated alfalfa yields in this district are 7410 kg/ha with below average management, 8650 kg/ha with average management and 11200 kg/ha with above average management. Hamlin (1983a) estimated that average dryland yields in northwestern Saskatchewan (which is adjacent to the study region and has a climate similar to Coronation, although slightly moister) are about 4035 kg/ha with average management and 4480 kg/ha with above average management. Table 4.16 lists predicted seasonal alfalfa yields at Coronation with a variety of different irrigation systems and management practices.

The alfalfa model predicted yields which are appropriate with average to above average management. For this reason, predicted yields often agreed well with experimental field trials. These field trials normally had yields better than those expected with average farm management. It was appropriate that the model predicted yields which are expected with above average farm management. The yield model assumed that soil fertility was not limiting to yield. This condition is probably rarely met on real farmland because forage crops are often

Table 4.16 Predicted Alfalfa Yields at Coronation

	Yield (kg/ha) mean	SD
Dryland	4105	1029
SCP soil I < 35% AM depletion	11009	579
SCP soil II < 50% AM depletion	8683	414
TCP (30 ha) soil I < 50% AM depl.	9333	422
SR (32 ha/lateral) soil I< 50% AM depl.	9113	574
SR (32 ha/lateral) soil III < 50% AM depl.	8614	592

not grown on the most productive soils nor often fertilized for maximum yield. Also the model did not include the lower alfalfa yields during the establishment year. Irrigation was managed optimally within the constraints imposed by the scheduling criteria and the physical limitations of the irrigation system. Finally, there was perfect uniformity of the irrigation across the field. Because of all the above reasons, the model should estimate yields which are expected with above average farm management.

Table 4.17 gives predicted alfalfa yields at Lacombe. Typical dryland farm forage yields (primarily alfalfa-grass mixtures) in the Lacombe district are about 3700 kg/ha (Peters et al. 1978). However, Peters et al. (1978) noted

Table 4.17 Predicted Alfalfa Yields at Lacombe

	Yield (kg/ha) mean	SD
dryland soil I	5614	1174
dryland soil III	5077	1383
TCP (106 ha) soil I < 50% AM depl.	9992	762
SCP soil II < 50% AM depl.	9168	414
HHT (64 ha) soil III < 50% AM depl.	9869	752

that forage yields were lower than those possible because farmers did not fertilize forage crops adequately since the forage stands did not respond well to fertilizer additions.

The model predicted it may, in fact, be economically optimal for farmers to underfertilize forage. There was a wide range in predicted dryland yields. To have no significant fertility limitations, the crop must be fertilized for expected use in years with average or above average moisture consumptive use. However, fertilizing at this rate would overfertilize in years with below average CU. In those years moisture conditions will control yield. Because alfalfa does not respond well to fertilizer additions and alfalfa does not have a high value per tonne, the farmer will have little or no economic return from fertilizer additions in years with below average precipitation (about one year out of two has below average precipitation). Therefore, fertilizing for below average CU is economically optimal. In this case, the alfalfa yield will be limited by soil fertility in most years.

The rationale for underfertilization is more persuasive in the Dark Brown soil zone (Coronation and Lethbridge) where highest predicted dryland yields are in the order of four times the lowest. The farmer's fertilizer dollar is better spent on grain crops, which are not only more responsive to fertilizer but also have a higher value per unit of production.

Each year the proportion of alfalfa in the stand tends to diminish. Alfalfa supplies a major proportion of its nitrogen requirements through a symbiotic relationship with microorganisms in the alfalfa roots. Older stands, which contain more non alfalfa plant species will not yield as well as younger stands (unless the older stand is well fertilized with nitrogen). The model assumes the stand is broken up and reseeded whenever the proportion of alfalfa in the stand falls significantly (every four to ten years). This condition may not always be met on farms.

Walker (1973) cited a number of dryland alfalfa yield trials at Lacombe where soil fertility did not limit yields. The average alfalfa yield for four years was 6384 kg/ha (range: 4493 to 9661 kg/ha) on loam soil and 3853 kg/ha (range: 3330 to 5802 kg/ha) on sandy loam soil. The measured difference between yields on the sandy loam and loam soils were far greater than those predicted by the model (see Table 4.17). There are several possible explanations for this difference: i) the actual sandy loam soil contained less AM in the spring than assumed for soil type III, ii) the real soil lost more moisture to deep percolation than modeled, iii) non-moisture related soil properties (e.g. pH and cation exchange capacity) lowered yields, and iv) the minimum limit for the second cut was greater than assumed. Raising the minimum yield before taking the second cut in the model to 2000 kg/ha would reduce average dryland yields on soil type III to 4678 kg/ha (5557 kg/ha on soil type I). With this latter modification, predicted yields were within 20% of the actual yields cited by Walker (1973).

In the model the second cut was taken providing it was above 1100 kg/ha. With this criteria, the second cut can be taken even if there was little precipitation during the latter part of the second growth. If the soil is very dry when the second cut is taken, then there would be minimal regrowth (for all locations the period following the second cut was the driest time during the simulation period). In this situation, the taking of a second alfalfa harvest is probably unwise if the farmer wants to leave the stand in healthy condition to overwinter. Also on mixed grain-cattle farms, the second alfalfa harvest can conflict with the labour needs of the grain harvest. In addition, alfalfa should not be harvested in September until after a killing frost to allow the stand to store adequate root reserves. The model frequently had the second cut of alfalfa at Lacombe and Edmonton occur in September immediately before a killing frost. A more complex criteria could be developed for determining whether to take the second alfalfa cut. The new criteria could be based on cumulative crop growth, AM at cutting time, and the date the stand becomes ready for harvest.

Walker (1973) noted that alfalfa yields at Lacombe on very well managed research plots are about 8000 kg/ha. This was about the predicted yield using the modified Wageningen method with a management factor of 1.0.

Three years of irrigation yield trials with well fertilized alfalfa were conducted at Grande Prairie (Alberta Agriculture 1981c). There are similarities in the climates of Grande Prairie and Lacombe in terms of temperatures, atmospheric water vapour pressure deficits, and precipitation. Also both Grande Prairie and Lacombe lie in agroclimatic zone 2H. The three year average dryland alfalfa yield at Grande Prairie was 5700 kg/ha (range 5000 to 7100 kg/ha). The average yield of all irrigation treatments was 9400 kg/ha (range 6600 to 12000 kg/ha). These yields conformed to the predicted yields at Lacombe.

Heywood et al. (1972) conducted a field level alfalfa yield trial for one year at Edmonton. The measured irrigated alfalfa yield was 9860 kg/ha and the dryland yield was 7580 kg/ha. Crop CU was measured between April 25 and September 27 which corresponds very closely to the dates between which predicted crop CU was normally totaled. For this period the measured CU of the irrigated alfalfa was 550 mm while the dryland CU was 372 mm. With a side roll irrigating 16 ha per lateral at 50% AM depletion (which was similar to irrigation in the experiment), the average predicted irrigated yield was 10153 kg/ha (range 9270 to 10915 kg/ha) with an average CU of 520 mm (range 435 to 586 mm). The average predicted dryland yield was 6024 kg/ha (range 3934 to 8307 kg/ha) with an average CU of 344 mm (range 257 to 474 mm). Therefore, measured values found by Heywood et al. (1972) fell within the midrange of predicted values.

Davies (1971) and Steed et al. (1969) studied yields from a number of irrigated farms in the Edmonton area. The irrigated soils were primarily sandy loams. Included were five crop-years of irrigated alfalfa. Growing alfalfa was a sideline for all these farmers. Irrigation of the alfalfa was not scheduled, but rather, carried out after potatoes had been irrigated. Hence only one or two irrigations of alfalfa were conducted each year. Table 4.18 lists the surveyed yields along with predicted yields. The actual dryland yields were from nine crop years. The predicted irrigated yields were for a side roll (32 ha/lateral) irrigating soil type III at 75% AM depletion using Edmonton weather. With 75% allowable AM depletion only one or two irrigations were conducted per season.

The predicted dryland alfalfa yield was considerably larger than that which the farmers actually harvested. The measured average dryland yield was low because in two years no cuts were taken. By comparison, the model predicted that at Edmonton there would always be sufficient rainfall and stored soil moisture for at least one cut. In 1968 one farmer took no cuts while another nearby farmer harvested 2500 kg/ha from one cut. Because alfalfa was a secondary crop, it was probably not valid to compare model yields (which assume above average management) with actual yields reported by Steed et al. (1969) and Davies (1971). Ignoring the dryland crop years with zero yield would increase the average dryland yield to 5045 kg/ha which is within 10% of the predicted dryland yield. Based on the results from irrigation at Edmonton, Davies concluded that farm alfalfa yields would be in the order of 9000 to 11200 kg/ha with a well managed irrigation system -- irrigated yields which were predicted by the model at Edmonton when AM was maintained less than 50% depleted.

Cairns and Bowser (1977) cited results from four years of well fertilized dryland alfalfa yield trials on Solonetzic soils at Vegreville. The average dryland yield was 4940 kg/ha. The predicted dryland yield on soil type II at Edmonton was 5539 kg/ha. The model predicted higher

Table 4.18 Comparison of Alfalfa Yields Reported in Steed et al. (1969) and Davies (1971) with Predicted Yields

	Yield (kg/ha)			
	measured		predicted	
	range	mean	range	mean
dryland	0 - 8968	3783	2621 - 8917	5583
irrigated	4360 - 8968	6570	3789 - 9250	7430

yields than the experimental but much of this difference can be attributed to the fact that Vegreville receives less precipitation throughout the year than Edmonton. Whereas mean annual precipitation at Edmonton is 467 mm, the corresponding value at Vegreville is 404 mm.

Bauder et al. (1978) analyzed the results of four years of irrigation trials of fertilized alfalfa in North Dakota. They calculated the WUE of dryland and irrigated alfalfa (allowing three levels of AM depletion). They found that alfalfa WUE was virtually independent of irrigation treatment. The treatment average WUE was 18.8 kg/ha/mm of ET. The WUE calculated from the irrigation trials of Korven and Wiens (1974) also do not exhibit any response to the irrigation treatment. The average WUE for this experiment was 17.1 kg/ha/mm. Likewise the WUE calculated from the irrigation trials of Hobbs et al. (1963) was independent of irrigation treatment. The average WUE for this latter experiment was 18.2 kg/ha/mm. Because WUE remains constant, this suggests that yield at one location is an approximately linear function of CU. Table 4.19 gives the predicted dryland and irrigated WUE for all modeled locations. The irrigated WUE was calculated from yield and CU data for a SCP irrigating soil type I whenever AM became more than 35% depleted. The estimated water use efficiencies estimated by the model agree well with observed values except that the model imparted a somewhat higher WUE to the irrigated crop. This suggests the model may, in fact, have been underestimating dryland yields relative to irrigated yields.

The predicted WUE of irrigated alfalfa was greater than dryland for two reasons: i) proportionately more of the dryland growth was predicted to be directed to root extension and ii) warm, sunny days favoured the irrigated stand. Because dryland yields were limited by the amount of precipitation, they were invariably less than irrigated yields. As a result equation (3.46) gave the irrigated crop a higher proportion of total growth which was above ground and harvestable. On warm, sunny days the temperature factor and photosynthetic flux were both greater than on cooler or more cloudy days. Therefore, predicted daily yields in relation to daily ET were greater on warm, sunny days. Because PET tended to be higher on these days and the irrigated soils normally had more AM than the dryland soils, the z factor produced greater daily

Table 4.19 Predicted WUE of Irrigated and Dryland Alfalfa

location	WUE (kg/ha/mm) dryland	irrigated
Coronation	15.88	19.01
Edmonton	16.90	19.67
Lacombe	15.63	19.22
Lethbridge	12.48	17.72

ET for the irrigated crop. On cooler and more cloudy days PET was generally less so the effect of the z factor was diminished. Therefore, estimated ET for the dryland and irrigated stands were more equal. In other words, the model predicted proportionately more dryland CU took place on cool and cloudy days than was the case for the irrigated crop. Consequently the WUE of the irrigated crop tended to be greater than the dryland crop.

Where June precipitation usually exceeded July precipitation (Lacombe and Lethbridge), yields were less in relation to consumptive use than where July precipitation was normally greater than June precipitation (Edmonton and Coronation). July precipitation was better timed in relation with crop moisture needs.

The model predicted that irrigated yields on soil types II and III were less than soil type I for one specific level of AM depletion. Both soil types II and III had considerably less AM capacity than soil type I. Hence, the crops growing on soil types II and III must be irrigated more frequently if the AM is not to become undesirably depleted. Hence, soil type I will generally have more favourable moisture conditions between irrigations than the other two soil types. Surprisingly, the yield advantage of soil type I remained even when irrigation is accomplished with a SCP irrigating at relatively low levels of AM depletion. For example, at Coronation with a SCP irrigating at 35% AM depletion, the predicted yield on soil type I is 11009 kg/ha (CU of 579 mm), 9422 kg/ha (CU of 479 mm) on soil type II, and 10363 kg/ha (CU of 532 mm) on soil type III.

The VSMB imparted the latter yield advantage to soil type I. If the entire root zone was moist, the effect of the k coefficients was to have more than one-half of ET occur from the upper one-quarter of the root zone. With the same amount of ET, the upper zones of soil types II and III became relatively drier than those of soil type I. As a consequence, the z factor reduced subsequent ET from the upper zones more for soil types II and III than for soil type I. Because ET was reduced, yield was also reduced. The assumption was made to apply the k coefficient modification for dry surface soil correction (equation (3.34)) when AM in the upper one-quarter of the root zone became more than 75% depleted. Applying equation (3.34) at lower levels of AM depletion for soil types II and III would probably eliminate some of the yield advantage of soil type I and better reflect rooting behavior in these soils.

Irrigated yields with the same allowable AM depletion and the same irrigation system were greater on soil type III than on soil type II. Soil type III has a slightly larger AM capacity than soil type II. Also, for the same amount of infiltrated water, the larger percolation coefficients of soil type II left less AM in the upper zones zones than is the case for soil type III. Therefore, some of the yield advantage of soil type III over soil type II can be attributed to the same factors which predicted larger yields on soil type I compared with soil types II and III. The lower half of the root zone of soil type II occasionally became saturated. This lowered ET and, thus, yields. Due to soil moisture properties, soil type II was the least productive soil under irrigation.

The model was probably underestimating the effects of poor internal drainage with soil type II. In reality, some of the excess water which cannot percolate below the root zone would collect in the lowest spots in the field. In these spots, insufficient aeration of the roots could damage or kill the alfalfa plants.

The dryland soil was predicted to become very dry by August. Figure 4.8 plots, for a typical year, predicted AM under alfalfa at Coronation for dryland conditions and when irrigated by a side roll (32 ha/lateral) at 35% AM depletion. At Coronation and Lethbridge it was quite common for the model to predict that there were several days when there was no AM in the entire root zone.

Depending on the irrigation system and scheduling criteria, the model usually predicted there will be more AM on October 15 in the root of irrigated soils compared with the dryland soils. Korven and Kilcher (1979) noted that irrigated soils consistently contained more AM in the fall and spring than adjacent dryland soils. Undoubtedly, some of the extra soil moisture present in the irrigated soils in the late fall is carrried forward into the next year.

The model predicted that a major portion of the greater yields expected with irrigation was due to larger yields of the second cut of the irrigated alfalfa. Figure 4.9 plots predicted daily yield for the year and irrigation management shown for Figure 4.8. The irrigated first cut yield was about twice that of the dryland first cut while the irrigated second cut was over four times as large as the dryland second cut.

Figure 4.9 shows that predicted regrowth following the second cut was substantially larger for the irrigated stand versus the dryland. The irrigated alfalfa should be more vigorous in the subsequent spring because of greater storage of food reserves in the roots and less winter kill. Heywood et al. (1972) found better spring growth of alfalfa irrigated the previous year compared with dryland alfalfa. Korven and Kilcher (1979) measured the proportion of alfalfa in irrigated and dryland alfalfa over a period

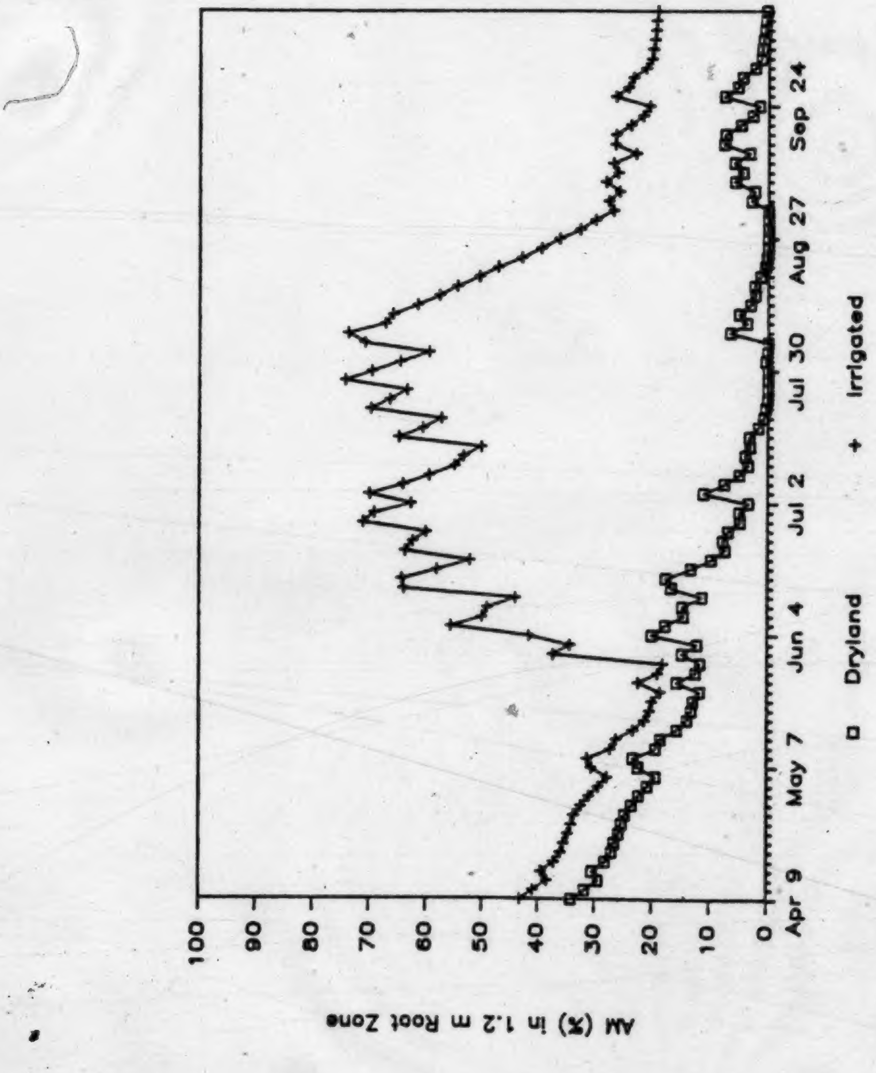


Figure 4.8 Predicted Available Soil Moisture under Irrigated and Dryland Alfalfa for One Year at Coronation

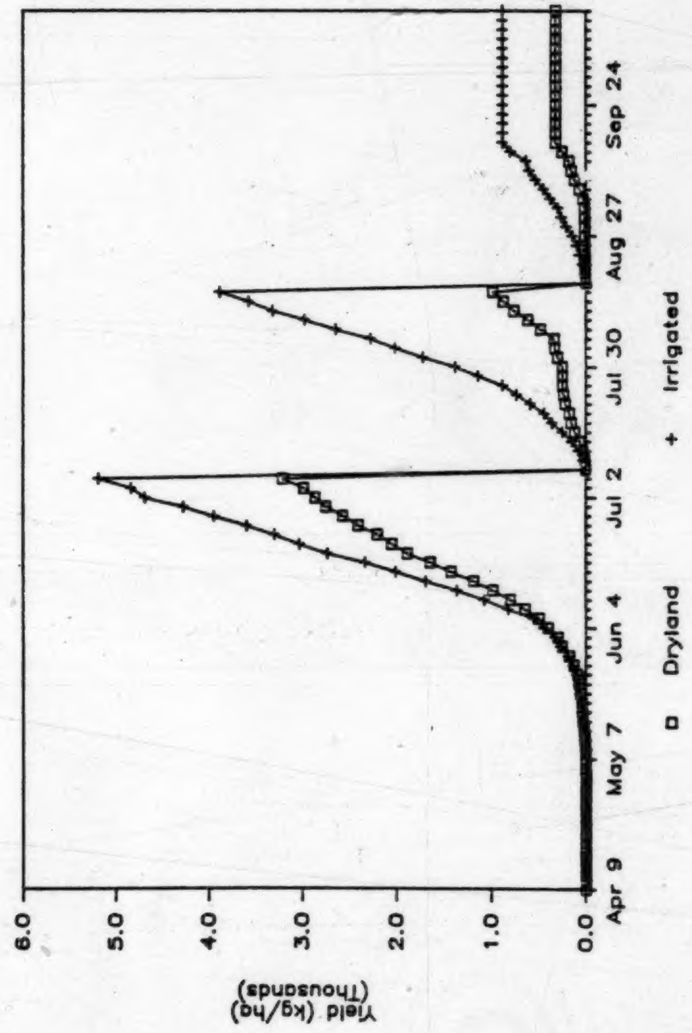


Figure 4.9 Predicted Cumulative Growth of Irrigated and Dryland Alfalfa for One Year at Coronation

of six years. They found that irrigated alfalfa stands contained more alfalfa plants than dryland stands.

The Wageningen yield method predicted the alfalfa yield was approximately a linear function of CU. Table 4.20 presents the calculated regression equation of seasonal field on CU. This regression equation was derived from ten years of dryland and irrigated yields at all four locations studied. The irrigated yields were for a side roll (32 ha/lateral) irrigating at 50% AM depletion. Also shown is the regression equation found by Bauder et al. (1978) for irrigation trials in North Dakota and the regression equation for model results for Lethbridge only. All equations are quite similar. A regression equation better explained the variation in yield when only one location was considered. The equation based on the model results indicated that yield will be more affected by CU than the equation developed by Bauder et al. (1978).

Predicted CU and yields for dryland conditions generally showed much more variation than for irrigated conditions. Figure 4.10 shows the pattern of predicted CU for 50 years of alfalfa at Coronation. Irrigation was accomplished with a SCP irrigating whenever AM became more than 35% depleted. Figure 4.11 shows the distribution of predicted seasonal yields for the same data set at Coronation. Figure 4.12 presents the predicted irrigation requirement for the above data set. In all cases the

Table 4.20 Regression Equations of Seasonal Alfalfa Yield on CU

Model, all locations: $Y=-1253.2 + 20.77 * CU$ $r^2 = 0.881$

Model, Lethbridge: $Y=-1957.0 + 19.51 * CU$ $r^2 = 0.953$

Bauder et al. (1978), North Dakota:

$Y= -833.1 + 15.94 * CU$ $r^2 = 0.966$

---

annual distribution can be described most simply by assuming a normal distribution.

Alfalfa yields were also predicted using the SIMFOY alfalfa yield method. Table 4.21 presents dryland and irrigated alfalfa yield estimates produced by the modified Wageningen and SIMFOY methods given the identical 25 years of weather. The management factor for both methods was 0.75.

The predicted irrigated yields were much higher than expected for farm irrigation at Edmonton. More importantly the predicted irrigated WUE was nearly double the predicted dryland WUE at both Edmonton and Lethbridge. There is no evidence in the literature to support the idea that alfalfa WUE is considerably greater when the crop is irrigated. For these reasons the SIMFOY yield method was rejected as an appropriate method to predict both dryland and irrigated yields.

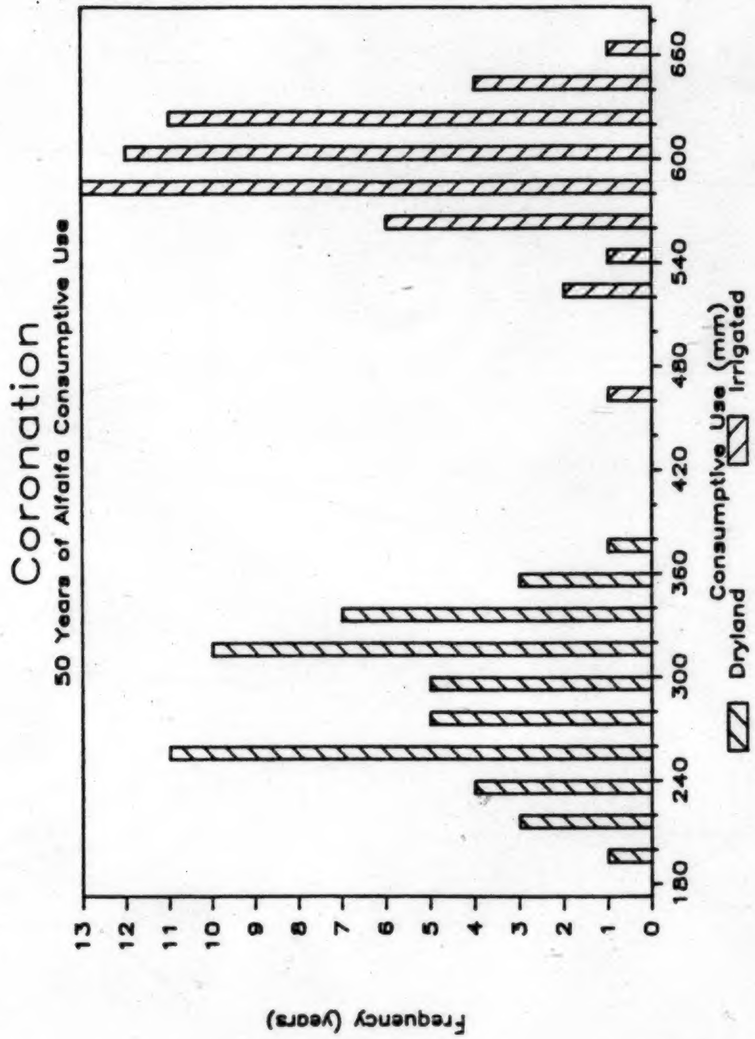


Figure 4.10 Predicted Growing Season Consumptive Use of Irrigated and Dryland Alfalfa at Coronation

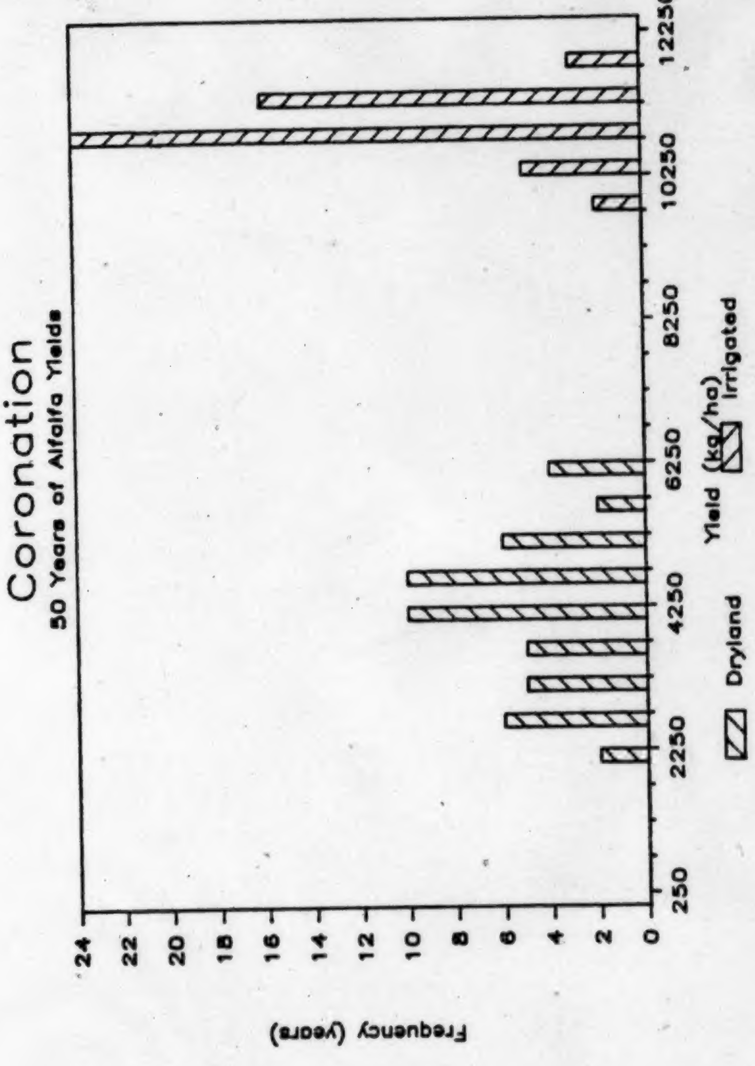


Figure 4.11 Predicted Seasonal Yields of Irrigated and Dryland Alfalfa at Coronation

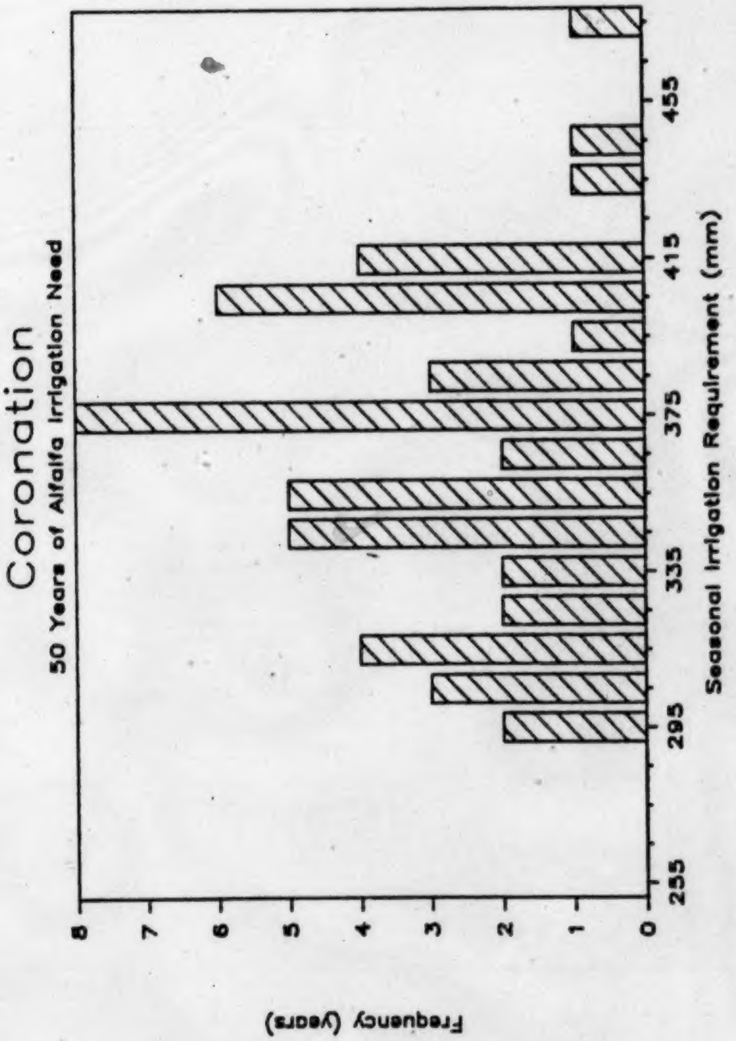


Figure 4.12 Predicted Annual Irrigation Requirement of Alfalfa at Coronation

Table 4.21 Comparison of Predicted Alfalfa Yields (kg/ha) and Water Use Efficiency (kg/ha/mm) of the Modified Wageningen Method with SIMFOY

	Wageningen			SIMFOY		
	Yield		WUE	Yield		WUE
	mean	SD		mean	SD	
Edmonton						
dryland	6024	1158	17.5	4608	1808	13.4
SR (16 ha/lat) < 50% AM depl.	10153	471	19.5	13354	693	25.4
TCP (106 ha) < 50% AM depl.	10284	460	19.3	12843	924	24.8
Lethbridge						
dryland	3668	1244	12.6	3041	1492	10.5
SR (16 ha/lat) < 50% depl.	9766	513	16.3	11840	821	19.7

SIMFOY yield estimates were based primarily on soil moisture. Yields predicted by the SIMFOY method decrease during any period when the AM in any of the soil in the root zone falls below 20% AM depletion. On the other hand, the modified Wageningen method was based on estimated ET. Using the VSMB, ET did not necessarily decrease if AM in part or all of the soil in the root zone was more than 20% depleted. Hence, the Wageningen method was less sensitive to soil moisture, per se, than SIMFOY. SIMFOY was developed for humid southern Ontario. SIMFOY could probably be calibrated to work either for dryland conditions on the Canadian Prairies or for irrigated conditions -- but not for both situations together without major modifications.

In conclusion, the VSMB provided good estimates of average CU. However, the variation in predicted CU was less than that experienced for real crops. The k coefficients after the second cut (including those used after the stand becomes dormant) may require modification. The modified Wageningen yield estimate produces reasonable estimates of alfalfa yields providing the stands are well managed (above average farm management including maintaining good soil fertility). The variation in annual yields predicted by the Wageningen method was less than that for real yields. The SIMFOY yield method is probably unsuitable for predicting both dryland and irrigated yields. The alfalfa development model could be improved.

4.2.4 Discussion of the Simulation of Wheat Yield and Moisture Use

Development of the wheat yield model proved to be very difficult. Dozens of variations of the Wageningen method were tried. The primary problem was constructing a yield model which would function satisfactorily using both Edmonton and Lethbridge weather.

However, despite the above, it was simpler to validate the model for dryland wheat yields because farm grown wheat is normally well managed in terms of soil fertility and weed control. In addition, wheat is often grown on the most productive soils.

As with alfalfa, the predicted variation in both yields and CU was less than that found in yield trials. This can be explained by the reasons described for alfalfa.

Korven and Wiens (1974) conducted yield trials of hard wheat using several different irrigation intervals at Swift Current. They used a side roll and irrigated at 50% AM depletion. CU was measured from the early spring to the late fall so corresponded closest with the total simulation CU from April 9 to October 15. Table 4.22 lists the experimental results along with results predicted by the model for Lethbridge using a side roll irrigating at 50% AM depletion with the same irrigation intervals used by Korven and Wiens (1974).

The model predicted significantly higher yields than that found by Korven and Wiens. The dryland wheat yield measured by Korven and Wiens was less than that found by other researchers at Swift Current. Baier (1973) reports the average dryland yield of hard wheat at Swift Current for 10 crop years was 1776 kg/ha. This supports the hypothesis that the yields measured by Korven and Wiens were less than those which could normally be expected.

The model gave a yield advantage to the 21 day irrigation interval over the 28 day interval which was not evident from the experiment of Korven and Weins (1974). Predicted total CU was less than measured for the 14 day irrigation interval. This probably indicates that actual ET after harvest was greater than the model predicted. Probably the k coefficient should be altered to allow more ET from the lower three-quarters of the root zone after harvest (the assumption was made that no ET occurs from the lower three-quarters of the root zone after harvest). This distortion was not evident for the other treatments because the soil was drier and less ET was possible. Total dryland ET was more for Lethbridge than Swift Current because Lethbridge receives more rainfall during May and June.

Three years of consumptive use and yield trials with fertilized hard wheat were conducted for the William Pearse Irrigation Project (Toogood 1963). The results of these trials along with model results with a SCP irrigating at Coronation (the actual trials were carried out 80 km south

Table 4.22 Comparison of Wheat Yields and Consumptive Use in Korven and Wiens (1974) with Predicted Results

	measured		predicted		
Treatment	range	mean	range	mean M=.75	mean M=.6
14 day irrigation interval					
yield kg/ha	2104-2632	2434	2490-3306	2943	2364
CU mm	550- 570	560		476	--
21 day irrigation interval					
yield kg/ha	1888-2485	2172	2081-3210	2739	2200
CU mm	450- 540	493		456	--
28 day irrigation interval					
yield kg/ha	2031-2431	2201	1770-3052	2510	2016
CU mm	420- 460	437		432	--
dryland					
yield kg/ha	606-1837	1097	792-2414	1648	1324
CU mm	220- 390	305		346	--

of Coronation) are presented in Table 4.23. The predicted yields showed excellent agreement with the measured yields if the management factor was reduced to 0.64. This indicates that the actual management was not as good as assumed or that other soil factors influenced yields. Toogood (1963) noted that there were emergence problems and that there was unexpectedly wide yield variation between replicates. The predicted CU was much less than that reported. The likely explanation was that CU was measured from early spring to late fall (the details of the experimental method were very sketchy). The predicted total ET from April 9 to October 15 for the dry, 75% AM depletion, 50% AM depletion, and 35% AM depletion runs were 290, 375, 406 and 434 mm respectively. These latter values agreed closely with the reported average crop moisture consumption.

Peters (1977) and Peters and Pettapiece (1981) analyzed Alberta Hail and Crop Insurance records of farmer reported yields for the period 1965 to 1974. They related dryland yields to soil type and agroclimatic zone. This comprises an excellent data set for validating predicted dryland wheat yields since it involves hundreds of crop years with normal farm management. When the yields were related to soil series, the yield could be related to a specific geographical area. Table 4.24 gives the reported average yields and predicted model yields for specific locations and agroclimatic areas. The standard deviation of farmer

Table 4.23 Comparison of Wheat Yields and Consumptive Use in Toogood (1963) with Predicted Results

	measured		predicted		
Treatment	range	mean	range	mean M= .75	mean M=.64
dryland					
yield kg/ha	646-2260	1500	975-2458	1704	1460
CU mm	224- 363	287	163- 293	202	--
irrigated at 75% AM depletion					
yield kg/ha	1280-2986	2292	2176-2900	2515	2154
CU mm	279- 429	369	259- 325	290	--
irrigated at 50% AM depletion					
yield kg/ha	1748-3369	2436	2597-3219	2928	2508
CU mm	350- 480	420	292- 354	319	--
irrigated at 35% AM depletion					
yield kg/ha	1762-3578	2710	3077-3569	3288	2816
CU mm	394- 495	442	318- 376	347	--

Table 4.24 Comparison of Wheat Yields in Peters (1977) and Peters and Pettapiece (1981) with Predicted Dryland Yields

Location	Approx. Soil Type	Reported Yield			Mod. Loc.	Predict. Dryland Yield (kg/ha)
		Stubble (kg/ha)	Fallow (kg/ha)	Average (kg/ha)		
Lethbridge	I	1473	2058	1766	Leth.	1697
Coronation	II	1190	1782	1486	Cor.	1543
ag-clim 1	I	2031	2703	2367	Edm.	2545
ag-clim 1	II	1520	2112	1816	Edm.	2272
Lacombe	I	--	--	2200	Lac.	2170
ag-clim 2A	I	--	--	2031	Cor.	1903
ag-clim 2H	II	--	--	1882	Lac.	1923

reported yields was generally about 50% more than the predicted standard deviation. The model assumed one constant level of farm management whereas the yield data included yields with different farm management practices. The effects of varying farm management was partially responsible for the underestimation of yield variation. However, in addition, the yield model did not accurately reproduce the real variation in annual yields.

Peters and Pettapiece (1981) compared the effect of soil texture on yield. They found that yields on medium textured soils were approximately equal to yields on fine textured soils (the fine textured soils had a slight yield advantage). Wheat yields on sands and sandy loams were only 84%, 83%, and 89% of yields on medium and fine textured soils in agroclimatic zones 1, 2A and 2H, respectively. Predicted yields on soil type III were 86%, 84%, and 90% of average yields on soil type I at Edmonton (agroclimatic zone 1), at Coronation and Lethbridge (agroclimatic zone 2A), and Lacombe (agroclimatic zone 2H), respectively. This indicates the model was ably predicting the effect of soil texture on wheat yields. (Because the model only considered moisture effects on yield, this also suggests that any yield disadvantage of coarse textured soils is primarily due to moisture conditions.) Peters and Pettapiece (1981) also compared yields on Solonetzic soils compared with Chernozems in agroclimatic zone 1. Generally wheat yields on Solonetzic soils were only 80 to 85% of those on Chernozems. By comparison, the model predicted the yield on soil type II were 89% of those on soil type I at Edmonton and Lacombe. Peters and Pettapiece (1981) found that the average yield of wheat in agroclimatic zone 1 on Solodized Solonetzic soils was 1836 kg/ha but on Solods (Solods are Solonetzic soils where the leaching process has partly or completely destroyed the Solonetzic hardpan so these soils have deeper root zones and better internal drainage than other Solonetzic soils) the average wheat yield was 2253 kg/ha. As mentioned previously Solonetzic soils are often pock marked with shallow pits. During wet periods water collects in these pits. Because internal drainage is poor, plants growing in the pits may be injured or killed due to excessive water in the root zone. Soil type II did take into account the impact of poor surface drainage. Therefore at Edmonton and Lacombe, soil type II represented Solonetzic soils with relatively deep root zones and some internal drainage (i.e. Solods). Predicted yields for soil type II were better estimates of yields on typical Solonetzic soils at Coronation and Lethbridge. At these locations the effect of poor surface drainage was less important because the weather was drier in terms of both atmospheric evaporative demand and rainfall.

Predicted yields at Edmonton were slightly greater than reported yields elsewhere in agroclimatic zone 1. However, Edmonton has particularly favourable natural moisture conditions compared with other areas in agroclimatic zone 1. Edmonton receives about 25 mm more precipitation over the year than most of the area included in agroclimatic zone 1. More importantly, this extra precipitation falls primarily during late June and July when it is of most benefit. Edmonton is as dry as other areas in agroclimatic zone 1 during harvest and seeding.

Predicted dryland wheat yields at Lethbridge appeared to be slightly underestimated. This suggests the effect of moisture stress was overestimated.

Overall, the model produced reasonable estimates of farm dryland wheat yields. The yields were approximately correct for wheat grown equally often on fallow and stubble soils -- which was the intent of the model.

Sonmor (1963) reviewed 12 years of irrigation yield trials of hard wheat in southern Alberta . The best average wheat yields were found when irrigation was conducted at about 50% AM depletion. This yield was 3600 kg/ha with a CU of 460 mm. At Lethbridge, the predicted yield with a SCP irrigating at 50% AM depletion was 3504 kg/ha with a CU of 417 mm (total CU from April 9 to October 15 was 528 mm). In southern Alberta, hard wheat irrigated with a well managed irrigation system has a CU about 95% of soft wheat (Korven and Randall 1975). Soft wheat has a CU of approximately 450 mm in southern Alberta (Alberta Agriculture 1982) thus giving hard wheat a CU of about 425 mm. This latter value for farm conditions was close to predicted CU in southern Alberta.

Linsley and Hamlin (1984) stated that average irrigated hard wheat yields in the Outlook area of Saskatchewan (which has a climate similar to Coronation) are 3160 kg/ha with average management and 3820 kg/ha with above average management. Table 4.25 presents irrigated yields at Coronation with a side roll and SCP. These values indicate the model results (with a management factor of 0.75) were most representative of yields with average farm management. This was appropriate since the model was also estimating dryland yields with normal farm management.

Table 4.25 Predicted Wheat Yields at Coronation

	Yield (kg/ha) mean	SD
Stationary Centre Pivot		
soil type I < 65% AM depletion	3045	262
soil type I < 50% AM depletion	3466	187
soil type I < 35% AM depletion	3760	142
soil type I < 25% AM depletion	3882	141
soil type II < 35% AM depletion	3081	203
soil type III < 35% AM depletion	3378	185
Side Roll (32 ha/lateral)		
soil type I < 65% AM depletion	2842	251
soil type I < 50% AM depletion	3043	246
soil type I < 35% AM depletion	3198	187
soil type I < 25% AM depletion	3286	192

de Jong and Cameron (1980) calculated the WUE of dryland wheat grown in field trials in Saskatchewan during the 1960's and 1970's. On Dark Brown soils the average WUE was 8.5 kg/ha/mm (standard deviation of 2.9 kg/ha/mm) on fallow and was 7.2 kg/ha/mm (standard deviation of 1.5 kg/ha/mm) on stubble. On Black soils the corresponding values were 7.6 kg/ha/mm (standard deviation of 2.7 kg/ha/mm) on fallow and 7.3 kg/ha/mm (standard deviation of

2.1 kg/ha/mm) on stubble. The University of Saskatchewan 1981 Guide to Farm Practice gives the WUE of irrigated hard wheat as approximately 9.9 kg/ha/mm. Table 4.26 lists the WUE of wheat for dryland and irrigated conditions calculated from model results at all locations considered.

The predicted water use efficiencies of wheat agreed well with measured values in Saskatchewan. Because the model produced good estimates of dryland yields, this partially validated dryland CU predicted by the VSMB. The model underestimated the WUE of wheat in the Dark Brown soil zone relative to the Black soil zone. This, again, suggests the model overemphasized the effect of moisture stress in the Dark Brown soil zone.

The predicted WUE of irrigated wheat was greater than dryland wheat partly because of the same warm, sunny day influence as described for alfalfa. In addition the model estimated more yield reduction due to moisture stress (as estimated by MSF) under dryland conditions compared with irrigated.

Table 4.26 Predicted Wheat Water Use Efficiency

	WUE (kg/ha/mm)	
Location	dryland	irrigated
Coronation	8.13	9.53
Edmonton	8.78	9.63
Lacombe	7.34	9.08
Lethbridge	7.01	8.86

The WUE of hard wheat for the experiment of Korven and Wiens (1974) were calculated. For these trials there was no discernible relationship between irrigation treatment and WUE.

Sonmor (1963) stated that hard wheat yields generally do not improve if allowable AM depletion is reduced to less than 50%. He also noted that the timing of precipitation has a greater effect of irrigated wheat yields than for most other crops. However, the model predicts significant yield improvements when reducing the allowable AM depletion. Table 4.25 presents predicted irrigated wheat yields at Coronation with a range of allowable AM depletion. The yield response to low levels of allowable AM depletion was most notable with a SCP. In a limited experiment with hard wheat, Hobbs and Krogman (1978) found WUE increased when irrigation water was applied with frequent light applications compared with the more conventional practice of irrigating at 50% AM depletion and irrigating to approximate field capacity. Since CU also increased with frequent light applications, this fact would give a significant yield advantage to irrigating with a SCP at low levels of AM depletion (since this produces frequent, relatively light applications). It is important to note that irrigation trials conducted during the 1950's and 1960's in southern Alberta frequently employed surface irrigation. Frequent, light applications are impractical with surface irrigation. Furthermore, centre pivot

irrigation in Alberta did not become important until the mid 1960's. Consequently, irrigation trials have not fully investigated the irrigation scheduling choices open to a farmer irrigating with a stationary centre pivot.
With a SCP, the irrigator has a wide choice of allowable AM depletions and an equally wide choice of how deep to wet the root zone. Further irrigation trials are needed to determine the optimal irrigation practices for a SCP.

Hinman (1974) and Bauer et al. (1965) found that the WUE of hard wheat is a function of both moisture stress and soil fertility. Reducing moisture stress (by irrigating) or increasing the quantity of plant available nitrogen and phosphorus increased WUE. Part of the yield advantage of fallow soils can be explained by the above relationship. During the fallow year organic matter is broken down which releases nitrogen and phosphorus for plant use. Therefore fallow soils are typically more fertile than stubble soils (unless stubble soils are very well fertilized). In addition, fallow soils usually contain more stored AM. Consequently, crops grown on fallow soils yield more than those on stubble soils not only because they have more moisture to consume but, as well, they can make more effective use of what moisture is available.

The Wageningen method summed daily yield components to arrive at seasonal yield. Therefore, one would expect the estimated number of days of actual growth would influence predicted yields. However, the effects of temperature and sunshine compensated for the effect of growing season length. In fact, the highest predicted potential irrigated wheat yields were at Lethbridge despite the fact that the model also predicted that wheat grown at Lethbridge has the fewest number of growing days from seeding to harvest.

A number of regression analyses were conducted on the the predicted model results. Table 4.27 lists the resulting regression equations. The irrigated results were for a SR (32 ha/lateral) irrigating at 50% AM depletion. Table 4.27 also presents the regression equation calculated by Bauer (1971) from analysis of many dryland yield trials in the Northern Great Plains of the United States and in southern Saskatchewan (equation (4.10)). There is a general similarity between equations (4.9) and equation (4.10). However Bauer's regression equation proposed that spring stored moisture and rainfall were of equal importance to dryland wheat yield while equation (4.10) suggested that the amount of rainfall was more important to yield than AM in the spring. Essentially, predicted yield was an almost linear function of CU.

In the drier locations (Coronation and Lethbridge), yield was positively correlated with spring stored moisture. Although the coefficient of determination (r^2) was small, it was significant at the 95% level of confidence (Snedecor and Cochran 1980). Even in years with below average precipitation the wheat crop could still

Table 4.27 Regression Equations of Yield on Moisture Availability

Nomenclature:

Y = yield (kg/ha)
R = precipitation during growing season (mm)
SSM = stored AM in the spring (mm)
CU = crop consumptive use (mm)

All Locations, dryland and irrigated:

$$Y = -459.2 + 9.672 * CU; \quad r^2 = 0.8206 \tag{4.6}$$

Coronation and Lethbridge, dryland:

$$Y = 599.7 + 7.066 * R; \quad r^2 = 0.6335 \tag{4.7}$$

$$Y = 876.6 + 8.895 * SSM; \quad r^2 = 0.2021 \tag{4.8}$$

$$Y = -176.3 + 6.888*SSM + 8.125*R; \quad r^2 = 0.8021 \tag{4.9}$$

Bauer (1971), dryland:

$$Y = -599.1 + 6.33 * SSM + 6.46 * R \tag{4.10}$$

Edmonton and Lacombe, dryland:

$$Y = 2191 + 0.837 * SSM; \quad r^2 = 0.0017 \tag{4.11}$$

---

yield well if there was substantial reserves of soil moisture for it to draw upon. This indicates the importance of summerfallowing in the Dark Brown soil zone to conserve moisture. The importance of spring stored soil moisture on dryland yield also confirms that seeding into dry stubble soils is hazardous unless rainfall is abundant. However, in the Black soil zone there was no significant correlation between yield and spring stored moisture. This suggests, in general, that summerfallowing in the Black soil zone to conserve moisture is not necessary. The model projected that final yield will be more determined by rainfall than spring stored soil moisture. However, the above is a simplification. In abnormally dry years at Edmonton and Lacombe, wheat yields were improved significantly if there was large reserve of spring stored moisture. Therefore, a risk averse farmer may still be be wise to summerfallow for moisture conservation in the Black soil zone. (There are other advantages to summerfallowing over continuous cropping -- weed control, reducing the need for commercial fertilizers, and spreading out the field work more evenly over the season.)

The model imparted a yield advantage to soil type I over soil types II and III (see Table 4.25). In addition, irrigated yields on soil type III were somewhat greater than those on soil type II. The explanation for these yield differences is the same as outlined for alfalfa.

A plot of cumulative yield for irrigated and dryland wheat versus time for a typical year at Coronation is shown in Figure 4.13. Irrigation was accomplished with a side roll (32 ha/lateral) irrigating at 50% AM depletion. No attempt was made to validate daily yield estimate since

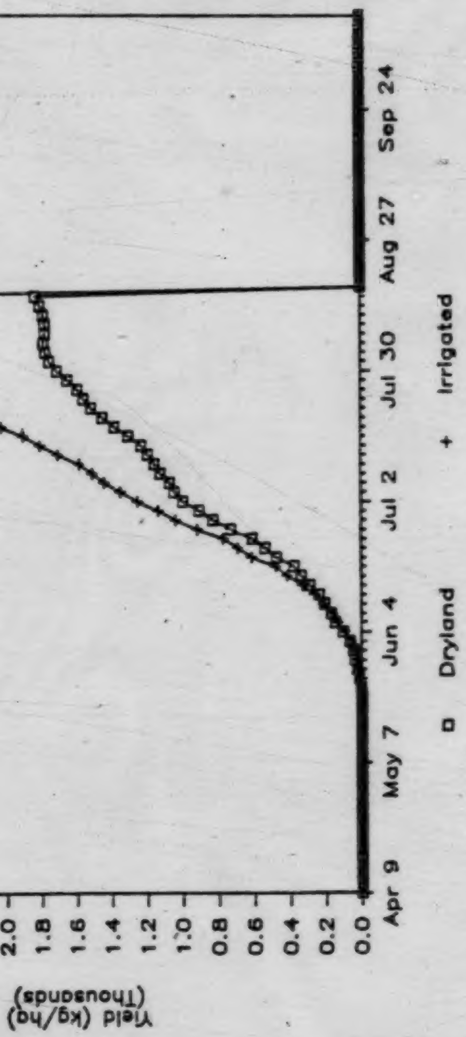


Figure 4.13 Predicted Cumulative Irrigated and Dryland Wheat Yield for One Year at Coronation

only seasonal yield was considered important. The growth curve exhibited the characteristic "S" shaped curve for annuals -- initially the rate of dry matter accumulation increased until the ripening stage when the rate of dry matter accumulation decreased to zero at ripe. Before emergence, the predicted cumulative yields were neglible. Because of the effect of the moisture stress factor, it was possible to have negative daily growth between the heading and hard dough stages. Figure 4.14 is a plot of soil moisture versus time for the same crop year as shown in Figure 4.13. In this year, there was a week of abnormally wet weather in late August. The model predicted dryland AM decreased throughout the growing season but rarely did the entire root zone become depleted of all AM.

As would be expected, the variation in yields and CU of dryland wheat was much greater than for irrigated wheat. Figure 4.15 portrays the distribution of dryland and irrigated wheat yields at Coronation. Figure 4.16 shows the distribution of wheat CU for the same data set shown in Figure 4.15. The distribution of net irrigation amounts is presented in Figure 4.17. As with alfalfa, these distributions approximate a normal distribution.

In conclusion, the wheat yield model provided reasonable estimates of dryland and irrigated yields which are expected with normal farm management. The effect of moisture stress in the Dark Brown soil zone may be overestimated. One change which could possibly improve

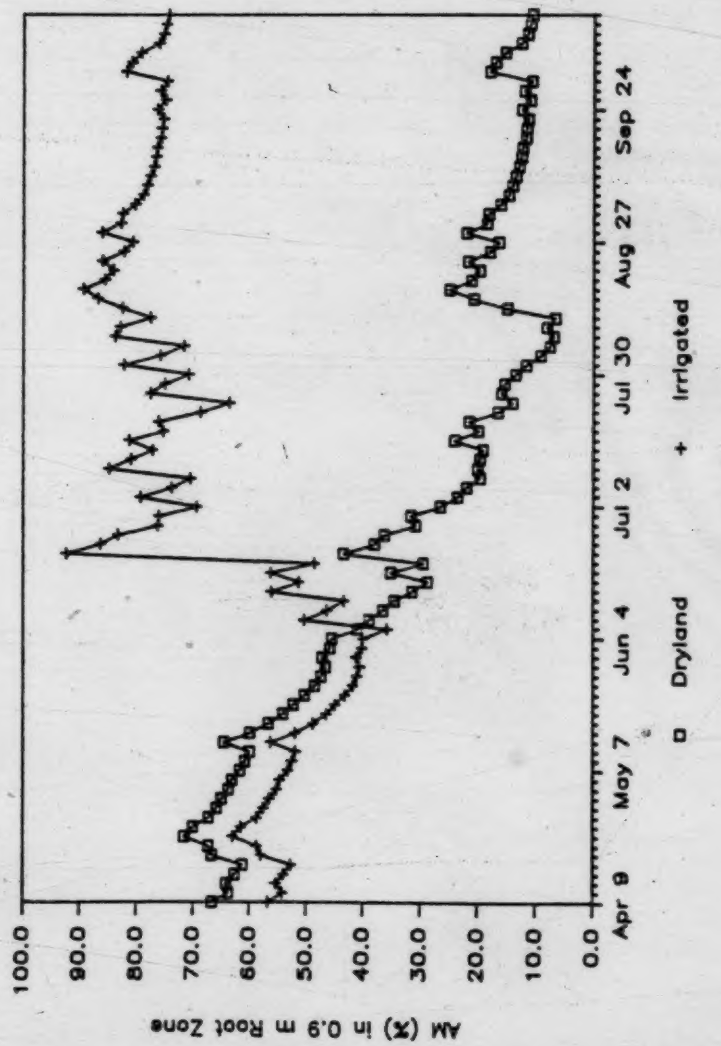


Figure 4.14 Predicted Available Soil Moisture Under Irrigated and Dryland Wheat for One Year at Coronation

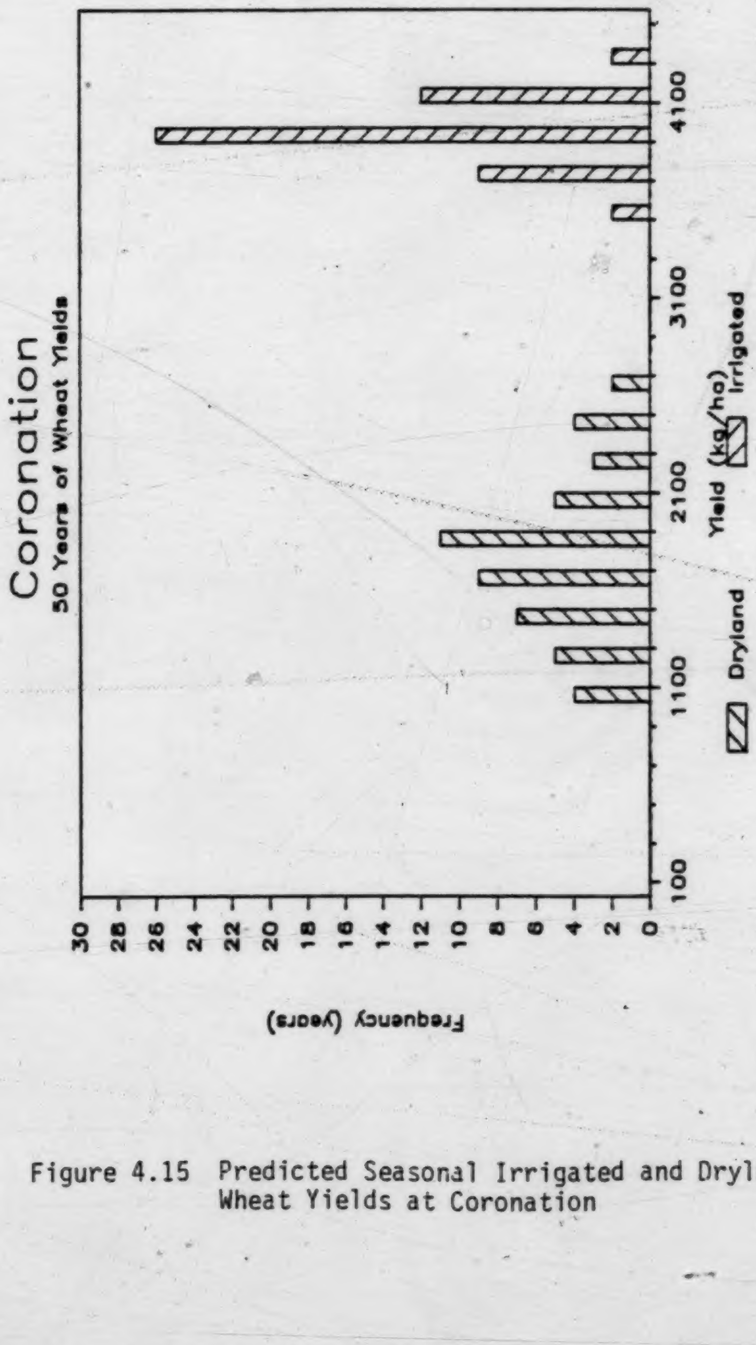


Figure 4.15 Predicted Seasonal Irrigated and Dryland Wheat Yields at Coronation

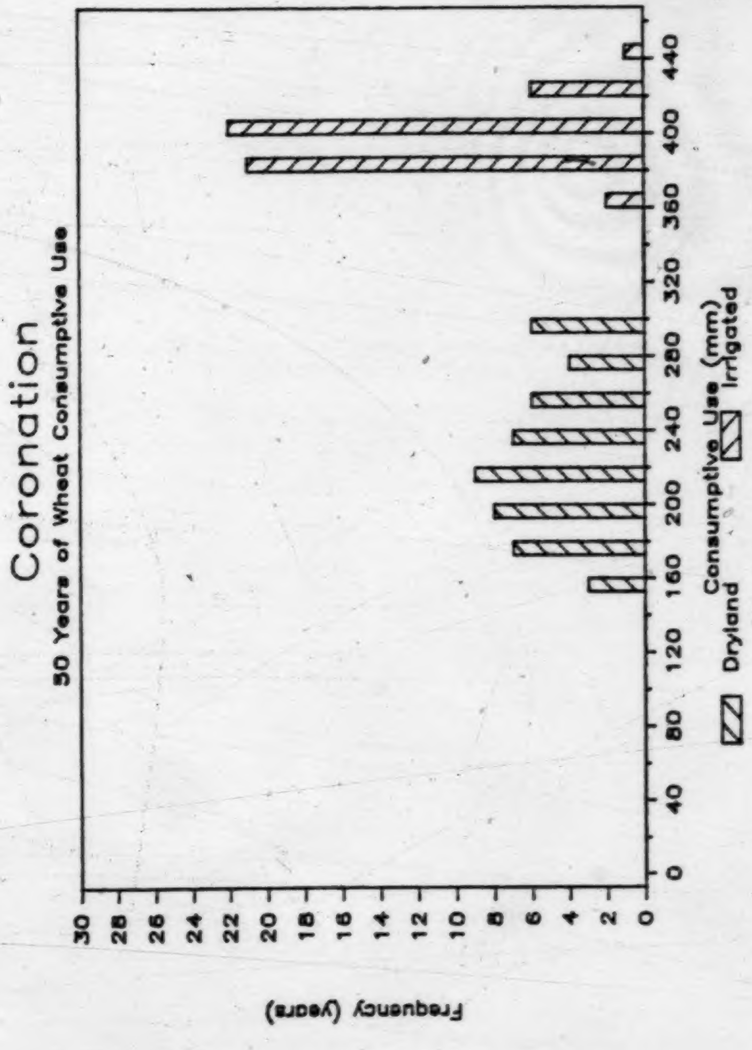


Figure 4.16 Predicted Seasonal Consumptive Use of Irrigated and Dryland Wheat at Corcnation

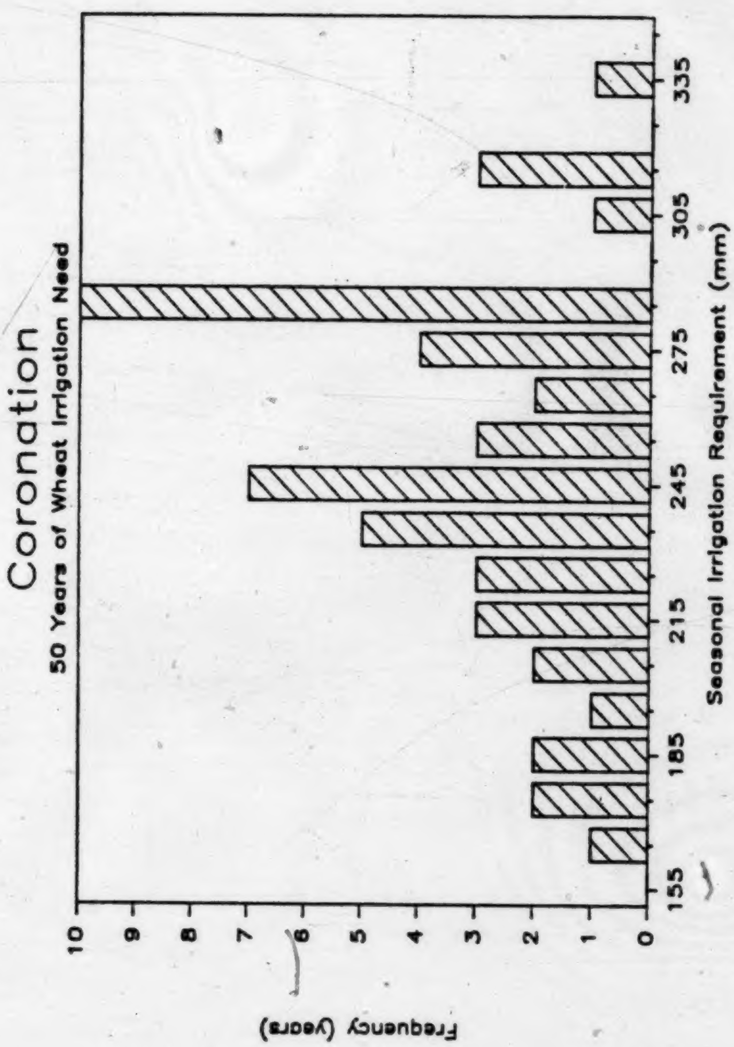


Figure 4.17 Predicted Net Annual Irrigation Requirement for Wheat at Coronation

this situation is to have ky (in equation 3.68) change gradually rather than in discrete steps as implemented in the model. The VSMB produced acceptable estimates of crop CU although the post-harvest k coefficients may require some modification.

4.2.5 Discussion of Soil Moisture Status on April 9

In reality nearly all ET will take place from April 9 to October 15 (the simulation period). Outside of these dates ET is minimal because there is essentially no root extraction of moisture, the soil surface is either frozen or snow covered, and PET is normally very small. Table 4.28 lists the predicted total dryland ET for the entire simulation season, the historically measured precipitation during the year and during the simulation period, the proportion of mean annual precipitation which becomes ET, and the proportion of precipitation from October 15 to April 9 (winter precipitation) which is implicitly assumed to infiltrate the soil and become ET. Although the starting soil moisture in the spring was assumed to be greater for wheat, the model predicted that alfalfa leaves the soil drier in the fall. Hence, the average total dryland ET for wheat was very similar to that predicted for alfalfa. The predicted total ET was reasonable within the constraints imposed by the amount of natural precipitation.

Table 4.28 Relationship Between Actual Precipitation and Predicted Total Dryland Evapotranspiration

Location	Historical Precipitation mean annual (mm)	Apr 9 - Oct 15 (mm)	Total ET (mm) Alfalfa	Wheat	Propor. annual precip of Tot. ET	Propor. winter precip in Tot. ET
Coronation	374	275	327	328	0.88	0.53
Edmonton	467	356	402	394	0.85	0.38
Lacombe	443	347	412	411	0.93	0.67
Lethbridge	424	---	353	346	0.82	----

Invariably, the model predicted the irrigated soils which had been cropped to wheat had considerably more soil moisture on October 15 than the dryland soil. Usually there was also a significant difference between fall soil moisture for irrigated and dryland alfalfa. Undoubtedly, some or all of this extra moisture in the fall would be carried over into the subsequent spring.

A major change could be made to the model to account for the effect of fall stored soil moisture. The model could be modified so that soil moisture for the entire year is modeled. Daily simulation of weather and soil moisture would need to start earlier in the spring and extend further into the fall. The process of soil freezing could be modeled and the amount of winter precipitation generated. Finally, the snowmelt and its infiltration into the soil could be simulated. With the above alterations, the model could carry the predicted amount of soil moisture at freeze-up over into the subsequent spring.

Soil moisture in the spring is a partial function of fall soil moisture in the previous year which, in turn, is a partial function of soil moisture in the spring of that year. Two or three simulated years would likely be required for the quantity of avaliable soil moisture in the spring and fall to reach equilibrium. The model results from these years would have to be discarded.

Another major advantage to simulating soil moisture for the entire year is that arbitrary soil moisture distributions for dryland soils in the spring would not have to be chosen. This may improve the ability of the model to predict dryland wheat yields. Finally, simulating soil moisture for the entire year would allow one to estimate the effect of different crop rotations on soil moisture and ultimately yields.

Unfortunately, the processes of overwinter soil moisture movement and the melting and infiltration of snow are poorly understood. Modeling these processes would be difficult and time consuming. In addition the model would be further complicated. The added complexity, along with the necessity of ignoring the first few simulated years, would also significantly increase the cost of using the model.

4.3 Model Sensitivity

Although no formal sensitivity analysis was conducted, a qualitative understanding of model sensitivity was acquired during the debugging and calibration stages of model development.

In general, simulating soil moisture and crop growth on a daily basis helped reduce model sensitivity to the small changes in the functional relationships or in inputs. Predicted results which were possibly overestimated during one period were likely underestimated during another period. Therefore, seasonal results were not overly sensitive to small model changes.

Essentially the model concentrated on simulating moisture movement through the atmosphere, plants and the soil. Consequently, the entire model was inherently sensitive to the precipitation generated by the weather submodel. Fortunately, the generated precipitation was an excellent approximation of historical precipitation patterns.

The k coefficients, z factors, and percolation coefficients in the VSMB must all be chosen by the modeler. The soil moisture storage served to buffer the effects of altering the k coefficients and z factors. For example, increasing the k coefficients increased daily ET immediately following a rain or irrigation. This dried the soil quickly, so on subsequent days, less ET can take place. Consequently, over several days, cumulative ET remained similar even if the k coefficients were changed significantly. Similarly, soil moisture storage buffered the effect of changing the z factors. The percolation coefficients did not have a pronounced effect on ET estimates (although increasing the percolation coefficients increased deep percolation). For all the locations considered, natural precipitation was normally less than potential crop demand. As a result, the model was not very sensitive to the choice of k coefficients, z factor, and percolation coefficients when only dryland conditions are modeled. By July, the dryland crops were primarily consuming the moisture from the last rain.

The yield models were quite sensitive to variations in the functional relationships. Predicted yields were proportional to the values of K, Cp, Hi, and M used in the modified Wageningen wheat and alfalfa yield models. The yield models were sensitive to varying the Ct and Cs relationships for either crop providing the average value of these factors changed during June, July, and August. Otherwise, the effect of varying the exact Ct and Cs functions was not apparent. The wheat yield model was very sensitive to the function and constants (especially ky) used to calculate the effect of moisture stress.

Because the net returns were frequently close to zero, the net returns appeared to be very sensitive to the values chosen for costs and crop value. For example, assume the average net returns are equal to zero when total costs for irrigation are $500/ha. If costs and prices were changed so that total costs increased by 10%, the average net returns would decrease to -$50/ha. On the other hand, if costs and prices were altered so that total costs decreased by 10% the net returns would become $50/ha. Similarly, the returns appeared to be sensitive to the predicted average yields. Consider the case where net returns are equal to zero with an irrigated wheat yield of 3200 kg/ha. A 10% decrease in predicted average yields would result in average net returns of -$55/ha. Of course a 10% increase in irrigated yields would produce an annual net return of $55/ha. The sensitivity of farm net income to relatively small changes in product prices and costs exists in the real world. As a result, this sensitivity can not be lessened.

4.4 Model Results

Daily ET, averaged from the start until the end of growth, for wheat and alfalfa grown on soil type I are listed in Table 4.29. The average irrigated ET were calculated for a SCP irrigating at 35% AM depletion. For a well watered crop (i.e. irrigated with a SCP at 35% AM depletion), the mean maximum daily ET for periods from seven to ten days was approximately equal to average Penman

PET for a dry day during the same period. Thus the seasonal maximum mean daily ET was dry day PET during July. This latter ET rate could be expected to occur about once each year (for a well watered crop) on soil type I and about once every second year on soil types II and III. The maximum average ET for one week to ten days was about the same for both wheat and alfalfa. Average peak daily ET for periods from one week to ten days were as high as 150% of average seasonal ET. The peak rate could be expected to take place about one year out of five on all three soil types. Alfalfa grown at Lethbridge or Lacombe were the exceptions to the above rule. At Lethbridge, average peak daily ET was approximately 165% of average seasonal ET while at Lacombe it was approximately 140% of average seasonal ET. Table 4.29 also lists the approximate average maximum and peak daily ET rates for Coronation, Edmonton,

Table 4.29 Predicted Daily ET

	Daily ET (mm/d)							
	Alfalfa				Wheat			
	Dryland	Irrigated			Dryland	Irrigated		
Location	mean	mean	max.	peak	mean	mean	max.	peak
Coronation	2.0	4.2	5.5	6.3	2.3	4.0	5.5	6.0
Edmonton	2.5	3.9	5.2	5.9	2.8	3.7	5.2	5.6
Lacombe	2.5	4.4	5.3	6.2	2.6	3.9	5.3	5.9
Lethbridge	1.8	4.5	7.0	7.5	2.6	4.9	7.0	7.4

Lacombe, and Lethbridge. As explained earlier the weather model was not generating the complete range of PET totals for ten day periods. Therefore, the real peak ET rates are probably greater than those predicted by the model. The average daily ET estimates predicted throughout the growing season at Lethbridge agreed well with measured average daily ET of wheat and alfalfa in southern Alberta (Krogman and Hobbs 1976).

To minimize moisture stress, the intermittent move system should supply sufficient water so that the crop can transpire at the maximum potential rate. If the irrigation system can not always apply water as fast as the crop could use it, the system is overextended. Table 4.30 lists the maximum area which can be irrigated with a side roll and HHT before soil AM may limit ET during midsummer for at least some of the irrigated area. As mentioned earlier, there is usually some rain during the irrigation interval in east central Alberta. Thus the problem of having an overextended irrigation system is primarily a concern at Lethbridge, but is also a concern in east central Alberta with soils with a relatively small root zone AM capacity.

Providing irrigation is started when the crop becomes no more than 50% depleted of available soil moisture, the stationary centre pivot will always permit maximum potential ET. When irrigating two positions, the TCP

Table 4.30 Safe Irrigated Area for Side Rolls and Hard Hose Travelers

	Soil Type				
	I		II	III	
Location & System	Alf.	Wh.	Alf.& Wh.	Alf.	Wh.
East Central Alberta (5.5 mm/d)					
side roll (ha/lat.)	42	31	16	24	18
hard hose trav. (ha/gun)	56	42	21	31	24
Southern Alberta (7.0 mm/d)					
side roll (ha/lat.)	33	24	12	19	14
hard hose trav. (ha/gun)	44	32	16	25	19

should normally supply potential crop ET. However, when towed between three positions, the TCP would be overextended for all locations during midsummer.

Both water drive centre pivots (with fixed revolution rates) and electric drive centre pivots (with variable revolution rates) were modeled. Generally the revolution rates had little effect on crop yield or CU. Most of the predicted results with pivot irrigation were based on pivot which could have revolution rates varying between 0.35 and 1.5 revolutions per day.

All the results were based on a management factor of 0.75. Increasing the management factor increases the difference between dryland and irrigated yields. Although total irrigation costs would remain constant, gross returns with a greater management factor would be larger. Consequently, increasing the management factor raises net returns. Similarly, decreasing the management factor lowers net returns.

Yield losses due to hail was not modeled. Obviously, hail can have a large impact on yield and net returns over the lifetime of an irrigation system. Hail insurance does not compensate completely for lost production. Hail is usually far more destructive to grain crops than to perennial forages. Hence, returns and yields for irrigated wheat will be overestimated on land prone to hail damage.

Model results are presented in the format shown for an example run in Table 4.31. The minimum allowable and desired proportions of AM capacity are only meaningful if one also considers the physical constraints imposed by the irrigation system. For the side roll and HHT there were definite minimum and maximum amounts which could be applied in one irrigation. The minimum allowed set time for a side roll was eight hours. During this time 50% of AM capacity could be applied. The maximum set time was 12 hours during which 77% of AM capacity could be applied. Similarly, the maximum set time for the HHT was 24 hours during which 50% of AM capacity was applied. The minimum set time was 12 hours during which 23% of AM capacity was applied. Consequently, many of the inputted allowable and desired levels of AM depletion were unrealistic. For example, consider a side roll which irrigated in eight hour sets with scheduling criteria which specified irrigation when AM was 50% depleted and continue irrigation until the AM reached 75% of AM capacity. Since this system applies 50% of AM capacity in one irrigation, if irrigation is started at 50% AM depletion, the soil will be brought up to about field capacity (rather than the desired 25% AM depletion). Furthermore, for all locations and crops, the soil generally had only one-half of AM capacity when irrigation was permitted to be started. Therefore, if the scheduling criteria required only 35% AM depletion, the system would begin irrigating as soon as allowed. However, the last part of the field to be irrigated would usually have more than 35% AM depletion. Depending on the irrigation interval, the irrigation system may not be able keep the soil at less than 35% AM depletion even after several irrigations. Generally, only a SCP could come close to satisfying the scheduling criteria exactly.

All runs involved 25 simulated seasons. Different weather patterns were produced by inputting a different initial seed number into the uniformly distributed random number generator. Over 25 years, there was little difference between results with different seed numbers. The exception to the above was average dryland yield. Average dryland wheat and alfalfa yields could vary as much as 10% between different 25 year weather patterns. The

Table 4.31 Explanation of Presentation of Predicted Results

CoA12[1] SR2[2] 32 ha[3] (200 mm)[4] 50%[5]<I[6]<100%[7]
(2,3,4)[8]: 3.0[9],3.0[10]
(846437)[11]

	mean		SD
Yield (kg/ha)			
cut 1	5084[12]	(2540)[13]	333
cut 2	3337	(1565)	597
total	8421	(4105)	740
CU[14] (mm)	451		50
WUE[15] (kg/ha/mm)	18.7		
Net Irrigation[16]	190		0
Labour[17] (h)	64		0
Oct 15 AM[18] (mm)	16		12
Deep Perc.[19] (mm)	4		3
Total Cost[20] ($/ha)	423		5
Net Returns ($/ha)	-78[21]	(-18.4%)[22]	41

Notes:

1) run code Co=Coronation (Ed=Edmonton, La=Lacombe, Le=Lethbridge)
   A=Alfalfa (W=Wheat)
   12=run number
2) irrigation system type SR2=two lateral side roll (SR1=one lateral side roll, HHT=hard hose traveler, SCP=stationary centre pivot, TCP=towable centre pivot)
3) total irrigated area
4) seasonal limit on accumulated net irrigation (given only if limiting)

Table 4.31 Explanation of Model Results (continued)

5) minimum allowable proportion of AM capacity in the root zone (the root zone for irrigation scheduling purposes). If possible, start irrigation when actual AM in the root zone is less than this proportion of AM capacity.
6) soil type
7) desired proportion of AM capacity in the root zone. If possible, net irrigation application is set such that the actual AM in the root zone after irrigation will equal this proportion of AM capacity in the root zone.
8) irrigation scheduling crop growth stages for which minimum AM (note 5) and desirable AM (note 7) apply (only given if different than 3,4,5 for wheat and 1,2,3,4 for alfalfa)
9) minimum number of sets which can be irrigated by one lateral (or one large gun) per day
10) maximum number of sets which can be irrigated by one lateral (or one large gun) per day
11) initial seed number for random number generator
12) irrigated yield
13) dryland yield
14) crop consumptive use from start of growth to end of growth
15) water use efficiency using CU as defined above
16) average net irrigation over entire irrigated area
17) total labour required for entire irrigated area (excluding labour to return side roll or HHT to starting set at the end of an irrigation and any labour required for maintenance and repairs)
18) available moisture in entire root zone on October 15
19) total deep percolation below the root zone from April 9 to October 15
20) total annual irrigation costs (as defined in section 4.5)
21) annual net return (as defined in section 4.5)
22) simple rate of return i.e. average annual net return over average total irrigation costs

reason for this behavior was that certain 25 year weather patterns had better timed precipitation than other 25 year weather patterns. Even a relatively small change in average dryland yield had a pronounced effect on net returns. Therefore, the dryland yield is shown along with the irrigated yields.

Because weather and stored soil moisture in the spring were identical, model runs sharing the same seed number can be compared directly. Any difference noted between irrigation practices using runs with the identical initial seed number was always noted when using another set of runs using a different initial seed number. Therefore, when the same seed number was used, even small differences in yields and returns can be considered significant. When irrigation practices were compared with runs with different initial seed numbers, the results must be compared statistically. The t-test indicates that, with 25 data points, sample means need to be about twice the average standard deviation apart to be considered statistically different at the 90% level of confidence. Examining several runs with different seed numbers suggested the above criteria was appropriate for estimating the significance of differences in average yields but not appropriate for other means (e.g. total net irrigation, October 15 AM, annual net returns, etc.). Means for all items except yield were consistently different for many runs with different initial seed numbers if they were more than one average standard deviation apart for one pair of model runs. Hence, when comparing runs with different initial seed numbers, mean yields were considered significantly different if they varied by more than two average standard deviations while all other means were considered significantly different if they differed by more than one average standard deviation.

As implemented, surface runoff only resulted when daily rainfall exceeded 25 mm. Since rains of this size are relatively infrequent, the amount of predicted runoff was in the order of a few millimetres per year. Generally, there was no significant difference between surface runoff from irrigated land compared with surface runoff from dryland soils. Therefore, surface runoff was not included in the presentation of model results.

The simple rate of return was defined as the ratio of average annual net returns to average total irrigation costs. Usually rates of returns are calculated as the ratio of net annual returns over the average annual fixed cost. The rationale for the latter ratio is that annual variable costs are paid out of annual income. The assumption was made that the revenues from irrigation would not be realized until approximately one year after the expenses have been incurred. Thus, the farmer must finance the annual variable costs for about one year. Consequently, the simple rate of return is a conservative estimate of equivalent interest rate which would be earned from the investment in irrigation. Where the primary objective of irrigation is to increase net farm income, the simple rate of return should probably be a least as great as competing investments (for example purchasing additional farmland after deducting interest charges). However, if the primary goal of irrigation is to reduce the effect of droughts then investing in irrigation may still be worthwhile even if the rate of return is less than other potential investments.

When the minimum allowable depletion of AM in the root zone was 50% or less the first irrigation in the season was called for about as soon as permitted in early June. The dates when subsequent irrigations were started depended on precipitation and the scheduling criteria.

4.4.1 Model Results for Alfalfa

As explained earlier the results for each 25 year run differed slightly when distinct initial seed numbers were used. Table 4.32 lists the predicted dryland results along with the the initial seed number used to generate the weather for 25 years.

Being the wettest location, Edmonton had the largest predicted average dryland yields as well as the largest amount of deep percolation and available moisture on October 15. Generally, predicted dryland deep percolation was very small. Most deep percolation occurred in soil type II because of the lowest root zone capacity for water and the most downward unsaturated flow. Because of natural moisture conditions and the effect of the soil cover factor, for all locations the average first cut yield was greater than the average second cut yield.

Many 25 year model runs for irrigated alfalfa at Coronation are listed in Table 4.33. These results used the format explained in Table 4.31. Runs CoA1 through CoA11 were all for soil type I irrigated with a stationary pivot. Irrigating to field capacity (CoA2) was less profitable than irrigating until AM reaches 85% of AM capacity in the root zone (CoA1). In other words, better returns were obtained if only the upper 85% of the root zone was kept wetted.

When irrigation was continued for both the first and second growths, the irrigated soils invariably contained more available moisture on October 15 than the dryland soils. If any of this moisture is carried over into the subsequent spring then the irrigated soils would contain more moisture in the early spring than assumed (i.e. that both the dryland and irrigated soil began with the same average amount of AM on April 9). Consequently, the irrigation requirement and variable costs of irrigation would be overestimated. For run CoA4 the irrigated soil contained an average of 79 mm more AM on April 9 than assumed for other runs (including CoA3). Compared with run

Table 4.32 Predicted Dryland Alfalfa Results

		Soil Type					
		I		II		III	
Loc.	result	mean	SD	mean	SD	mean	SD
Cor.	seed number	(275638)		(383838)		(483741)	
	Yield (kg/ha)						
	cut 1	2543	642	2074	576	2207	682
	cut 2	1589	826	1673	899	1623	836
	total	4132	1190	3746	1050	3830	1141
	CU (mm)	271	44	250	45	252	40
	WUE (kg/ha/mm)	15.3		15.0		15.2	
	Oct 15 AM (mm)	9	10	8	8	6	8
	Deep Perc. (mm)	0	0	0	1	0	0
Edm.	seed number	(846437)		(846437)		(846437)	
	Yield (kg/ha)						
	cut 1	3462	682	3069	776	3121	802
	cut 2	2540	650	2470	894	2462	873
	total	6002	1036	5539	1278	5583	1286
	CU (mm)	355	55	330	56	331	57
	WUE (kg/ha/mm)	16.9		16.8		16.9	
	Oct 15 AM (mm)	22	21	24	20	25	18
	Deep Perc. (mm)	0	0	2	5	1	4
Lac.	seed number	(575757)		(575757)		(575757)	
	Yield (kg/ha)						
	cut 1	3376	854	2940	1010	3062	1008
	cut 2	2238	729	1955	923	2015	926
	total	5614	1174	4894	1282	5077	1383
	CU (mm)	339	56	305	58	318	58
	WUE (kg/ha/mm)	16.6		16.0		16.0	
	Oct 15 AM (mm)	12	9	16	13	16	13
	Deep Perc. (mm)	0	0	2	2	0	0
Leth.	seed number	(575757)		(575757)		(846437)	
	Yield (kg/ha)						
	cut 1	2661	855	2416	772	2815	871
	cut 2	751	773	491	754	571	906
	total	3412	1146	2907	885	3386	1462
	CU (mm)	270	66	250	57	279	64
	WUE (kg/ha/mm)	12.6		11.6		12.1	
	Oct 15 AM (mm)	4	7	7	9	4	6
	Deep Perc. (mm)	0	0	1	1	0	0

CoA3, the extra 79 mm of moisture reduced annual irrigation requirements by 86 mm and increased average net returns by $42/ha. Thus, net annual irrigation was reduced by the approximate amount soil moisture in the irrigated soils on April 9 exceeded that normally assumed. Given the variable costs of applying water ($0.4335/ha/mm for a SCP), the reduced net irrigation application would reduce annual irrigation costs by $37/ha. Therefore, almost all the improvement in average annual net returns were explained by the decrease in variable costs. The remainder of the improvement in annual net returns were attributable to slightly greater irrigated yields resulting from the moister soil in early spring. The small yield increase was probably due to slightly better moisture conditions throughout the growing season.

If all the extra moisture in the irrigated soils on October 15 were carried forward into the next year, then the April 9 AM would be greater than assumed. In fact the quantity of additional moisture in the irrigated soil on April 9 would equal the difference between AM present in the irrigated and dryland soils. However, some of the extra moisture could easily be lost as deep percolation from October 15 to April 9. In this case, AM in the irrigated soils on April 9 would be somewhere between that assumed and that adding the entire difference between AM in irrigated and dryland soils on October 15. Postulating that essentially all additional October 15 AM is carried forward to April 9 permits one to make an approximate allowance for the effect of this extra moisture in the irrigated soils in the next year. Net irrigation requirement would be approximately reduced by the amount of the additional April 9 AM (i.e. additional to that assumed) and annual net returns would be increased by the amount that variable irrigation costs would be lessened due to decreased irrigation. For example, for runs CoA1 and CoA2 the irrigated soils contained about 50 mm more AM on October 15 compared with adjacent dryland soils (see Table 4.32). Carrying all of this water forward into the next spring would reduce annual net irrigation needs by 50 mm and thereby increase average annual net returns approximately $21/ha.

Runs CoA5 and CoA6 show the effect of having a severely restricted irrigation water supply (only sufficient water for about one full irrigation). In this case the gross returns from irrigation did not pay the costs of irrigation. Irrigation should not be contemplated where there is likely to be insufficient irrigation water supply.

Irrigation during the first growth only (run CoA7) was far more profitable than irrigation only during the second growth (run CoA8). Any irrigation water not used in the first growth was used during the second growth. Thus, irrigating during the first growth increased both the first and second cut yields while irrigation only during the second cut improved only the second cut yield.

A stationary centre pivot permits frequent, light applications. Runs CoA9 and CoA10 are results when the irrigation scheduling criteria were applied only to the upper one-half of the root zone. For example, irrigation in run CoA9 was started when the the AM in the upper 50% of the root zone reached 50% of AM capacity in that portion of the root zone and irrigation was stopped when the upper half of the root zone reached field capacity. The above criteria tends to force the irrigator to use frequent, relatively small applications of water. This practice used irrigation water very efficiently because there was no predicted deep percolation and October 15 AM was not much more than that present in dryland soils. However, because there was no deep percolation, maintaining only the upper one-half of the root zone moist could lead to salt accumulations in the root zone. Where salinization is not a concern, applying frequent, light irrigations is a technique which can be employed to use irrigation water more efficiently. Pohjakas (1981) found that irrigators in southern Alberta irrigate only so that the upper one-half to two-thirds of the root zone was kept moist. Pohjakas found no evidence that this practice was leading to salinization of the root zone. The model results indicates the farmers using frequent, light irrigations are following a good irrigation practice (Pohjakas states that the practice of maintaining only the upper portion of the root zone moist will produce yields far less than potential yields -- the model results disagree with this latter conjecture).

Allowing AM depletion exceeding 50% made the SCP uneconomical (run CoA11 versus run CoA3). For run CoA12 irrigation water supply was limited and the irrigation season was not started until about mid June. Although this was a labour saving irrigation practice, there was no return for the labour which was invested. Even after making allowances for the effect of fall soil moisture (i.e. assuming all the extra moisture in the irrigated soil on October 15 is carried forward into the next season), neither run CoA11 or CoA12 were profitable relative to dryland farming.

A TCP was not much more profitable than a SCP (run CoA13 versus run CoA3) and certainly involves more labour over the season. Also, irrigating 106 ha of alfalfa with a TCP produces far more forage than would be needed by almost all farming operations. Consequently most of the production would have to be sold off-farm. Runs CoA14 to CoA16 demonstrate three strategies for dealing with a moderate limitation on irrigation water supply. Run CoA14 delayed irrigation by permitting greater AM depletion (i.e. waiting for rain). Run CoA15 involved irrigation as usual until the the seasonal supply was exhausted while run CoA16 delayed the irrigation season until mid June. Although there was no clear advantage of one strategy over another, run CoA15 was slightly better. Permitting more AM depletion (run CoA14) increased labour needs because there was less likelihood of rain forcing the system to irrigate one field several times in succession. If irrigation water were supplied from a surface reservoir, then not delaying the irrigation season would be the best strategy. All reservoirs lose some water from evaporation and most reservoirs also lose water through seepage. On the Canadian Prairies, many surface reservoirs for private irrigation would be filled by runoff in the early spring. Therefore, it is desirable to use the stored water as quickly as feasible, to minimize unwanted losses. Consequently, delaying the irrigation season in not recommended. In addition, the model predicts marginally higher yields and returns by not delaying the irrigation season. With the TCP, the model predicted there was not a major penalty in terms of yields or net returns from permitting greater than 50% AM depletion (run CoA17 versus run CoA13).

A number of irrigation management strategies were tried for a two lateral side roll irrigating 64 ha. These are runs CoA18 through CoA22. Runs CoA19 and CoA20 demonstrate the effect of changing the allowable set times. For run CoA19 the set times varied between 8 and 12 hours (depending on the irrigation application called for) while for run CoA20 irrigation was accomplished using only eight hour sets. Using eight hour sets was more profitable at the expense of demanding more physical labour. If the extra October 15 AM of the irrigated soil was carried forward into the spring, mean irrigation needs for runs CoA19 and CoA20 would be reduced about 65 mm and average annual net returns would be increased about $29/ha. Runs CoA18, CoA21 and CoA22 involved different levels of allowable AM depletion. There was little change in either predicted irrigated yields or annual net returns as allowable AM depletion was altered. With ample labour, 50% AM depletion with eight hour sets was optimal. However, if labour is scarce (as it normally is) allowing 35% AM depletion or allowing 50% AM depletion along with set times up to 12 hours were optimal. Krogman and Hobbs (1976) noted that most irrigators in southern Alberta who use side rolls permit greater than 50% AM depletion. The model results suggest that this may not necessarily be a bad practice for irrigated alfalfa where labour for irrigation is limited.

Both runs CoA21 and CoA22 demonstrate that the irrigation system was not able to keep all the soil above 50% AM depletion. If the soil was kept above the allowable depletion, there would have been a large amount of deep percolation because each eight hour set would be applying water in excess of field capacity. Obviously, then, the soil usually had more than 35% AM depletion when irrigation was started in June. By the time the last set on the field was irrigated, the soil was drier still. With the 14 day irrigation interval of the system, even after several irrigations the system could not increase AM much above 50% AM depletion. The main effect of specifying allowable depletions less than 50% was to force irrigation to start as soon as possible and compel the irrigator to irrigate on each available day during the late spring and summer.

Runs CoA23 to CoA26 show the effect of varying the area irrigated with a one lateral side roll. The variability in yield was approximately the same for the 24 and 32 ha systems but increased with irrigated area for the 48 and 64 ha systems. The reason for this is that the 48 and 64 ha systems were overextended while the other two systems were not. The most profitable system was the 64 ha system. This system required the same hours of labour and the same volume of irrigation water as the 48 ha system but yet produced larger average annual net returns. Because of the relatively high costs to apply water, the HHT was uneconomical compared with the centre pivots or the side roll (runs CoA27 and CoA28).

Although dryland yields were less on soil type II than on soil type I, the predicted returns from irrigation were not greater because the irrigated yields were also less on soil type II (run CoA29 versus CoA1). Permitting large AM depletion was particularly unprofitable relative to dryland farming (75% AM depletion for run CoA30). The model predicted the irrigated soil type II did not contain appreciably more AM on October 15 than the dryland soils. Therefore the possible carryover of fall soil moisture for soil type II would not change irrigation requirements or returns significantly in the next year.

The 220 m long TCP has relatively large fixed costs per hectare and so was typically the least profitable irrigation system. Run CoA31 was especially uneconomical because it also involved a suboptimal irrigation scheduling criteria.

Soil type III was predicted to be more responsive to irrigation than soil type II. Applying frequent, light irrigations to alfalfa with a SCP was profitable at Coronation (run CoA32). However, irrigation with the side roll was not as profitable as for soil type I (run CoA33 versus run CoA20). The reason for this was that soil type III could not store as much water and so became undesirably depleted of AM between irrigations. Irrigation of soil type III with the HHT was also uneconomical. As with soil type II, there would not be much change in irrigation needs or annual net returns resulting from carrying over the extra October 15 AM into the next season.

In general the normal weather at Edmonton does not have prolonged dry spells. Therefore irrigation at Edmonton was not generally profitable relative to dryland crop production. Table 4.34 presents a number of runs for irrigated alfalfa at Edmonton. Assuming all the extra October 15 AM was carried forward into the next year, the only systems which would break even are the 400 m long TCP irrigating two circles (run EdA3) and the two lateral side roll irrigating 64 ha (run EdA10). However, in neither case would the simple rate of return be competitive with other investment opportunities (simple rate of return of 2.1% and 1.2% for runs EdA3 and EdA10, respectively). Stopping the irrigation system early in dry years did not have a significant effect on either yields or net returns (run EdA4 versus EdA3). However, the above practice did reduce labour demands significantly. Consequently, stopping irrigation a few weeks early in drier than average years may be an optimal irrigation practice in the Edmonton area. Irrigating alfalfa at Edmonton did not appear to be a worthwhile way to increase net farm income over that possible with dryland farming.

Lacombe tends to be drier than Edmonton after the first week in July. Therefore, irrigating alfalfa at Lacombe was more economical than at Edmonton. Table 4.35 contains many model runs for irrigated alfalfa at Lacombe. Runs LaA1 and LaA2 show the effect of manipulating the starting available soil moisture on April 9. On average, the irrigated soil for run LaA2 contained an additional 74 mm of AM than the irrigated soil for other runs (including run LaA1). The irrigation requirement was reduced by about the amount of the additional April 9 AM. The average annual net returns were increased by the saved variable irrigation costs. The irrigated soils invariably contained more AM on October 15 than the dryland soils. If any of this extra soil moisture is carried forward into the spring then the assumed April 9 soil moisture distribution underestimates the actual amount of AM in the spring. If all the extra soil moisture on October 15 is carried forward the effect can be estimated easily. Irrigation requirements in the next year will be reduced approximately by the difference between dryland and irrigated available soil moisture on October 15. The annual variable irrigation costs will be reduced and annual net returns raised since less water will be applied.

Runs LaA3 to LaA6 were for a 400 m long TCP irrigating two circles. A minor restriction on irrigation water supply did not reduce yields and returns greatly (run LaA4 versus LaA3). The minor restriction meant that in drier than average years the irrigation season was cut short by a few weeks. As was found at Edmonton, this practice appears to be optimal when labour is limited.

A two lateral side roll irrigating 64 ha of alfalfa was the most profitable system at Lacombe. There was no statistical difference between returns and yields allowing 65% AM depletion (run LaA7) versus 50% AM depletion (run LaA8). Assuming all the extra moisture in the irrigated soil on October 15 is carried forward into the next year the annual irrigation requirement for run LaA8 would be reduced about 80 mm and increase average annual net returns to $37 bringing the simple rate of return to 15%.

The 220 m long TCP was unprofitable because of relatively high fixed costs per hectare (run LaA9). Soil type II was less responsive to irrigation than soil type I (runs LaA10 and LaA11).

Irrigating alfalfa on soil type III only during the latter part of the first growth and during the beginning part of the second growth may be a satisfactory method of reducing the time spent irrigating (run LaA12 versus LaA13). The net returns were not reduced significantly by following this practice. With the side roll, trying to maintain less than 50% AM depletion did not significantly improve net returns compared with just trying to maintain 50% AM depletion (run LaA14 versus LaA13). Furthermore, irrigating soil type III at low levels of AM depletion resulted in a very large amount of deep percolation.

Irrigating alfalfa at Lethbridge was quite profitable. Table 4.36 gives the model results for irrigated alfalfa at Lethbridge. For farmers belonging to irrigation districts, the costs will be different from those assumed. These farmers will not be faced with the extra assumed fixed and pumping costs required to raise the water to field level. However, these latter cost savings are partially offset by the irrigation districts' water charges -- about \$25/ha to \$37/ha per year. Therefore the average annual net returns for farmers belonging to an irrigation district in the Lethbridge area will be somewhat greater than predicted by the model.

When irrigating with a SCP, the optimal scheduling criteria was to allow about 35% AM depletion before irrigating (runs LeA1 to LeA4). With the same proportionate level of AM depletion, the returns irrigating soil types II and III were similar to those irrigating soil type I (run LeA5 versus LeA1 and LeA6 versus LeA2). The lower predicted dryland yields on soil types II and III were balanced by lower predicted dryland yields on the latter two soil types relative to soil type I.

With a two lateral side roll irrigating 32 ha, there was little difference in yields, net returns, or labour needs between run LeA7 which allowed 50% AM depletion and run LeA8 which allowed only 35% AM depletion. Therefore, with the latter system, the optimal scheduling criteria would be to allow 50% AM depletion in the soil at the starting set before commencing irrigation. Since no third cut was harvested, it was very unprofitable to continue irrigation past the second cut (run LeA12).

The two lateral side roll irrigating 67.3 ha had equivalent returns to a well managed SCP but required much more physical labour (run LeA9 versus LeA2). Irrigating only during the first growth was profitable with an overextended side roll (run LeA10). Likewise, irrigating during both the first two growing periods was profitable with an overextended side roll. However, considering labour needs, the model indicated that the SCP was the most attractive irrigation system in the Lethbridge area. The rising popularity of the centre pivot among irrigators in southern Alberta supports the model predictions.

Table 4.33 Predicted Irrigated Alfalfa Results at Coronation

CoA1 SCP 65%<I<85% (383838)

	mean		SD
Yield (kg/ha)	10887	(4192)	434
CU (mm)	562		38
WUE (kg/ha/mm)	19.4		
Net Irrigation (mm)	347		43
Total Labour (h)	25		3
Oct. 15 AM (mm)	58		30
Deep Perc. (mm)	7		3
Total Cost ($/ha)	504		28
Net Returns ($/ha)	20	(4.0%)	65

CoA2 SCP 65%<I<100% (383838)

	mean		SD
Yield (kg/ha)			
cut 1	5926	(2461)	271
cut 2	4804	(1731)	255
total	10730	(4192)	335
CU (mm)	564		42
WUE (kg/ha/mm)	19.0		
Net Irrigation (mm)	374		46
Total Labour (h)	21		3
Oct. 15 AM (mm)	65		27
Deep Perc. (mm)	17		7
Total Cost ($/ha)	515		30
Net Returns ($/ha)	-3	(-0.6%)	55

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA3 SCP 50%<I<75% (846437)

	mean		SD
Yield (kg/ha)	10007	(4105)	425
CU (mm)	536		27
WUE (kg/ha/mm)	18.7		
Net Irrigation (mm)	314		35
Total Labour (h)	16		2
Oct. 15 AM (mm)	44		18
Deep Perc. (mm)	2		1
Total Cost ($/ha)	484		18
Net Returns ($/ha)	-12	(-2.5%)	55

CoA4 SCP 50%<I<75% average April 9 AM in irrigated soil=144 mm (846437)

	mean		SD
Yield (kg/ha)	10082	(4105)	408
CU (mm)	544		31
WUE (kg/ha/mm)	18.5		
Net Irrigation (mm)	228		41
Total Labour (h)	18		3
Oct. 15 AM (mm)	38		17
Deep Perc. (mm)	2		1
Total Cost ($/ha)	448		26
Net Returns ($/ha)	30	(6.8%)	63

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA5 SCP (100 mm) 65%<I<100% (365455)

	mean		SD
Yield (kg/ha)	6983	(4182)	760
CU (mm)	381		40
WUE (kg/ha/mm)	18.3		
Net Irrigation (mm)	100		0
Total Labour (h)	5		0
Oct. 15 AM (mm)	5		5
Deep Perc. (mm)	0		0
Total Cost ($/ha)	364		17
Net Returns ($/ha)	-140	(-38.5%)	41

CoA6 SCP (100 mm) 65%<I<100% (2,3,4) (365455)

	mean		SD
Yield (kg/ha)	7034	(4182)	764
CU (mm)	381		40
WUE (kg/ha/mm)	18.5		
Net Irrigation (mm)	100		0
Total Labour (h)	5		0
Oct. 15 AM (mm)	5		5
Deep Perc. (mm)	0		0
Total Cost ($/ha)	364		17
Net Returns ($/ha)	-136	(-37.4%)	41

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA7 SCP 65%<I<100% (2) (393847)

	mean		SD
Yield (kg/ha)			
cut 1	5607	(2739)	370
cut 2	3332	(1438)	608
total	8940	(4178)	759
CU (mm)	470		49
WUE (kg/ha/mm)	19.0		
Net Irrigation (mm)	226		45
Total Labour (h)	11		2
Oct. 15 AM (mm)	22		23
Deep Perc. (mm)	9		4
Total Cost ($/ha)	436		20
Net Returns ($/ha)	-55	(-12.6%)	57

CoA8 SCP 65%<I<100% (3) (393847)

	mean		SD
Yield (kg/ha)			
cut 1	2957	(2739)	663
cut 2	4000	(1438)	370
total	6957	(4178)	861
CU (mm)	430		43
WUE (kg/ha/mm)	16.2		
Net Irrigation (mm)	179		14
Total Labour (h)	12		1
Oct. 15 AM (mm)	32		27
Deep Perc. (mm)	2		3
Total Cost ($/ha)	398		18
Net Returns ($/ha)	-175	(-44.0%)	49

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA9 SCP 75%<I<100% upper 50% of root zone only (575757)

	mean		SD
Yield (kg/ha)	10455	(3983)	416
CU (mm)	542		35
WUE (kg/ha/mm)	19.3		
Net Irrigation (mm)	303		27
Total Labour (h)	24		3
Oct. 15 AM (mm)	26		17
Deep Perc. (mm)	0		0
Total Cost ($/ha)	485		30
Net Returns ($/ha)	33	(6.8%)	63

CoA10 SCP 50%<I<100% upper 50% of root zone only (575757)

	mean		SD
Yield (kg/ha)	8837	(3983)	462
CU (mm)	479		39
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	232		27
Total Labour (h)	14		2
Oct. 15 AM (mm)	19		15
Deep Perc. (mm)	0		0
Total Cost ($/ha)	440		27
Net Returns ($/ha)	-45	(-10.2%)	60

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA11 SCP 35%<I<50% (333333)

	mean		SD
Yield (kg/ha)	9204	(4105)	440
CU (mm)	492		29
WUE (kg/ha/mm)	18.7		
Net Irrigation (mm)	248		30
Total Labour (h)	12		2
Oct. 15 AM (mm)	25		12
Deep Perc. (mm)	0		0
Total Cost ($/ha)	448		18
Net Returns ($/ha)	-41	(-9.0%)	58

CoA12 SR2 32 ha (200 mm) 50%<I<100% (2,3,4): 3.0,3.0
(846437)

	mean		SD
Yield (kg/ha)			
cut 1	5064	(2540)	333
cut 2	3337	(1565)	597
total	8421	(4105)	740
CU (mm)	451		50
WUE (kg/ha/mm)	18.7		
Net Irrigation (mm)	190		0
Total Labour (h)	64		0
Oct. 15 AM (mm)	16		13
Deep Perc. (mm)	4		3
Total Cost ($/ha)	423		5
Net Returns ($/ha)	-78	(-18.4%)	41

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA13 TCP 106 ha 50%<I<65% (275638)

	mean		SD
Yield (kg/ha)	8906	(4132)	680
CU (mm)	491		30
WUE (kg/ha/mm)	18.1		
Net Irrigation (mm)	241		29
Total Labour (h)	80		11
Oct. 15 AM (mm)	38		21
Deep Perc. (mm)	0		0
Total Cost ($/ha)	366		18
Net Returns ($/ha)	16	(4.4%)	39

CoA14 TCP 106 ha (200 mm) 35%<I<65% (275638)

	mean		SD
Yield (kg/ha)	8331	(4132)	722
CU (mm)	454		37
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	192		16
Total Labour (h)	80		11
Oct. 15 AM (mm)	20		14
Deep Perc. (mm)	0		0
Total Cost ($/ha)	339		19
Net Returns ($/ha)	-3	(-0.9%)	40

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA15 TCP 106 ha (200 mm) 50%<I<65% (275638)

	mean		SD
Yield (kg/ha)	8435	(4132)	859
CU (mm)	459		42
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	198		6
Total Labour (h)	64		12
Oct. 15 AM (mm)	20		14
Deep Perc. (mm)	0		0
Total Cost ($/ha)	343		15
Net Returns ($/ha)	1	(0.3%)	35

CoA16 TCP 106 ha (200 mm) 50%<I<65% (2,3,4) (275638)

	mean		SD
Yield (kg/ha)	8386	(4132)	866
CU (mm)	459		42
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	198		7
Total Labour (h)	65		14
Oct. 15 AM (mm)	21		15
Deep Perc. (mm)	0		0
Total Cost ($/ha)	342		23
Net Returns ($/ha)	-2	(-0.6%)	34

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA17 TCP 106 ha 35%<I<60% (275638)

	mean		SD
Yield (kg/ha)	8639	(4132)	517
CU (mm)	473		24
WUE (kg/ha/mm)	18.3		
Net Irrigation (mm)	221		36
Total Labour (h)	92		14
Oct. 15 AM (mm)	27		16
Deep Perc. (mm)	0		0
Total Cost ($/ha)	355		27
Net Returns ($/ha)	6	(1.6%)	50

CoA18 SR2 64 ha 35%<I<85% (275638)

	mean		SD
Yield (kg/ha)	8437	(4132)	636
CU (mm)	486		29
WUE (kg/ha/mm)	17.4		
Net Irrigation (mm)	258		43
Total Labour (h)	168		14
Oct. 15 AM (mm)	59		29
Deep Perc. (mm)	1		1
Total Cost ($/ha)	319		25
Net Returns ($/ha)	25	(7.9%)	43

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA19 SR2 64 ha 50%<I<100%: 2.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	8608	(4132)	749
CU (mm)	498		36
WUE (kg/ha/mm)	17.3		
Net Irrigation (mm)	306		41
Total Labour (h)	122		8
Oct. 15 AM (mm)	81		35
Deep Perc. (mm)	16		5
Total Cost ($/ha)	407		20
Net Returns ($/ha)	11	(2.7%)	45

CoA20 SR2 64 ha 50%<I<100%: 3.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	9113	(4132)	612
CU (mm)	515		31
WUE (kg/ha/mm)	17.7		
Net Irrigation (mm)	300		53
Total Labour (h)	194		17
Oct. 15 AM (mm)	67		32
Deep Perc. (mm)	7		3
Total Cost ($/ha)	409		28
Net Returns ($/ha)	49	(12.0%)	42

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA21 SR2 64 ha 65%<I<85%: 3.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	9430	(4132)	555
CU (mm)	530		29
WUE (kg/ha/mm)	17.8		
Net Irrigation (mm)	349		45
Total Labour (h)	226		15
Oct. 15 AM (mm)	89		35
Deep Perc. (mm)	19		6
Total Cost ($/ha)	434		27
Net Returns ($/ha)	50	(11.5%)	46

CoA22 SR2 64 ha 75%<I<100%: 3.0,3.0 (483741)

	mean		SD
Yield (kg/ha)	9634	(4352)	526
CU (mm)	539		30
WUE (kg/ha/mm)	17.9		
Net Irrigation (mm)	371		23
Total Labour (h)	232		8
Oct. 15 AM (mm)	82		23
Deep Perc. (mm)	22		5
Total Cost ($/ha)	384		24
Net Returns ($/ha)	38	(9.9%)	49

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA23 SR1 24 ha 50%<I<65%: 2.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	9283	(4132)	615
CU (mm)	516		29
WUE (kg/ha/mm)	18.0		
Net Irrigation (mm)	302		40
Total Labour (h)	71		9
Oct. 15 AM (mm)	56		27
Deep Perc. (mm)	9		4
Total Cost ($/ha)	476		24
Net Returns ($/ha)	-64	(-13.4%)	45

CoA24 SR1 32 ha 50%<I<65%: 2.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	9067	(4132)	574
CU (mm)	511		27
WUE (kg/ha/mm)	17.7		
Net Irrigation (mm)	298		34
Total Labour (h)	95		11
Oct. 15 AM (mm)	59		26
Deep Perc. (mm)	7		3
Total Cost ($/ha)	410		24
Net Returns ($/ha)	-15	(-3.6%)	46

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA25 SR1 48 ha 50%<I<65%: 2.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	8384	(4132)	701
CU (mm)	483		35
WUE (kg/ha/mm)	17.4		
Net Irrigation (mm)	260		27
Total Labour (h)	118		13
Oct. 15 AM (mm)	51		24
Deep Perc. (mm)	3		3
Total Cost ($/ha)	324		23
Net Returns ($/ha)	16	(4.9%)	45

CoA26 SR1 64 ha 50%<I<65%: 2.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	7368	(4132)	826
CU (mm)	434		42
WUE (kg/ha/mm)	17.0		
Net Irrigation (mm)	194		24
Total Labour (h)	118		15
Oct. 15 AM (mm)	33		18
Deep Perc. (mm)	1		1
Total Cost ($/ha)	255		22
Net Returns ($/ha)	37	(14.5%)	43

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA27 HHT 32 ha 50%<I<65%: 1.0,2.0 (275638)

	mean		SD
Yield (kg/ha)	9888	(4132)	408
CU (mm)	533		24
WUE (kg/ha/mm)	18.6		
Net Irrigation (mm)	302		46
Total Labour (h)	111		18
Oct. 15 AM (mm)	47		23
Deep Perc. (mm)	1		1
Total Cost ($/ha)	478		33
Net Returns ($/ha)	-142	(-29.7%)	59

CoA28 HHT 64 ha 50%<I<65%: 1.0,2.0 (275638)

	mean		SD
Yield (kg/ha)	8658	(4132)	785
CU (mm)	485		37
WUE (kg/ha/mm)	17.9		
Net Irrigation (mm)	248		29
Total Labour (h)	146		25
Oct. 15 AM (mm)	40		21
Deep Perc. (mm)	0		0
Total Cost ($/ha)	338		25
Net Returns ($/ha)	-39	(-11.5%)	50

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA29 SCP 65%<II<85% (383838)

	mean		SD
Yield (kg/ha)			
cut 1	5194	(2074)	315
cut 2	4228	(1673)	324
total	9422	(3764)	417
CU (mm)	479		30
WUE (kg/ha/mm)	19.7		
Net Irrigation (mm)	254		39
Total Labour (h)	13		2
Oct. 15 AM (mm)	13		15
Deep Perc. (mm)	17		3
Total Cost ($/ha)	456		34
Net Returns ($/ha)	-2	(-0.4%)	65

CoA30 SCP 25%<II<85% (383838)

	mean		SD
Yield (kg/ha)	7642	(3746)	361
CU (mm)	408		31
WUE (kg/ha/mm)	18.7		
Net Irrigation (mm)	169		33
Total Labour (h)	11		2
Oct. 15 AM (mm)	10		11
Deep Perc. (mm)	6		2
Total Cost ($/ha)	403		28
Net Returns ($/ha)	-92	(-22.8%)	52

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA31 TCP 30 ha 35%<I<60% (275638)

	mean		SD
Yield (kg/ha)	8639	(4132)	517
CU (mm)	473		24
WUE (kg/ha/mm)	18.3		
Net Irrigation (mm)	221		36
Total Labour (h)	92		14
Oct. 15 AM (mm)	27		16
Deep Perc. (mm)	0		0
Total Cost ($/ha)	485		27
Net Returns ($/ha)	-125	(-25.8%)	50

CoA32 SCP 65%<III<85% (575757)

	mean		SD
Yield (kg/ha)			
cut 1	5649	(2201)	295
cut 2	4714	(1322)	222
total	10363	(3523)	358
CU (mm)	532		38
WUE (kg/ha/mm)	19.5		
Net Irrigation (mm)	295		26
Total Labour (h)	22		2
Oct. 15 AM (mm)	16		17
Deep Perc. (mm)	2		6
Total Cost ($/ha)	485		18
Net Returns ($/ha)	63	(13.0%)	54

Table 4.33 Irrigated Alfalfa at Coronation (continued)

CoA33 SR2 64 ha 50%<III<100%: 3.0,3.0 (483741)

	mean		SD
Yield (kg/ha)	8614	(3830)	592
CU (mm)	480		30
WUE (kg/ha/mm)	17.9		
Net Irrigation (mm)	291		28
Total Labour (h)	244		12
Oct. 15 AM (mm)	20		12
Deep Perc. (mm)	47		14
Total Cost ($/ha)	345		25
Net Returns ($/ha)	-22	(-6.4%)	48

CoA34 HHT 48 ha 65%<III<100%: 1.0,2.0 (483741)

	mean		SD
Yield (kg/ha)	9183	(3830)	548
CU (mm)	500		27
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	282		27
Total Labour (h)	143		17
Oct. 15 AM (mm)	18		12
Deep Perc. (mm)	21		10
Total Cost ($/ha)	398		27
Net Returns ($/ha)	-53	(-13.3%)	54

Table 4.34 Predicted Irrigated Alfalfa Results at Edmonton

EdA1 SCP 65%<I<85% (575757)

	mean		SD
Yield (kg/ha)	11318	(6700)	317
CU (mm)	559		25
WUE (kg/ha/mm)	20.2		
Net Irrigation (mm)	287		48
Total Labour (h)	17		3
Oct. 15 AM (mm)	95		25
Deep Perc. (mm)	13		10
Total Cost ($/ha)	454		37
Net Returns ($/ha)	-85	(-18.7%)	68

EdA2 SR2 32 ha 50%<I<100%: 2.0,3.0 (113232)

	mean		SD
Yield (kg/ha)	10153	(6534)	471
CU (mm)	520		28
WUE (kg/ha/mm)	19.5		
Net Irrigation (mm)	269		35
Total Labour (h)	92		6
Oct. 15 AM (mm)	99		30
Deep Perc. (mm)	15		10
Total Cost ($/ha)	437		28
Net Returns ($/ha)	-83	(-19.0%)	51

Table 4.34 Irrigated Alfalfa at Edmonton (continued)

EdA3 TCP 106 ha 65%<I<85% (275638)

	mean		SD
Yield (kg/ha)			
cut 1	5453	(3030)	431
cut 2	4831	(2927)	281
total	10284	(5957)	460
CU (mm)	533		28
WUE (kg/ha/mm)	19.3		
Net Irrigation (mm)	265		42
Total Labour (h)	84		16
Oct. 15 AM (mm)	84		30
Deep Perc. (mm)	8		6
Total Cost ($/ha)	366		32
Net Returns ($/ha)	-20	(-5.5%)	56

EdA4 TCP 106 ha (200 mm) 65%<I<85% (275638)

	mean		SD
Yield (kg/ha)	9762	(5957)	681
CU (mm)	506		35
WUE (kg/ha/mm)	19.3		
Net Irrigation (mm)	197		11
Total Labour (h)	54		10
Oct. 15 AM (mm)	48		36
Deep Perc. (mm)	5		6
Total Cost ($/ha)	331		38
Net Returns ($/ha)	-26	(-7.9%)	42

Table 4.34 Irrigated Alfalfa at Edmonton (continued)

EdA5 TCP 45 ha 50%<III<75% (684932)

	mean		SD
Yield (kg/ha)	9868	(6041)	383
CU (mm)	476		30
WUE (kg/ha/mm)	20.7		
Net Irrigation (mm)	168		32
Total Labour (h)	87		18
Oct. 15 AM (mm)	42		26
Deep Perc. (mm)	5		8
Total Cost ($/ha)	353		21
Net Returns ($/ha)	-47	(-13.3%)	60

EdA6 TCP 30 ha 50%<III<75% (684932)

	mean		SD
Yield (kg/ha)	10239	(6041)	329
CU (mm)	492		30
WUE (kg/ha/mm)	20.8		
Net Irrigation (mm)	187		36
Total Labour (h)	68		15
Oct. 15 AM (mm)	44		26
Deep Perc. (mm)	6		7
Total Cost ($/ha)	465		23
Net Returns ($/ha)	-129	(-27.7%)	66

Table 4.34 Irrigated Alfalfa at Edmonton (continued)

EdA7 HHT 48 ha 50%<III<100%: 1.0,2.0 (684932)

	mean		SD
Yield (kg/ha)	10076	(6041)	385
CU (mm)	490		34
WUE (kg/ha/mm)	20.6		
Net Irrigation (mm)	203		35
Total Labour (h)	84		14
Oct. 15 AM (mm)	52		25
Deep Perc. (mm)	14		14
Total Cost ($/ha)	432		22
Net Returns ($/ha)	-90	(-20.8%)	65

EdA8 SR2 64 ha 25%<III<100%: 2.0,3.0 (113232)

	mean		SD
Yield (kg/ha)	7430	(5946)	332
CU (mm)	384		31
WUE (kg/ha/mm)	19.3		
Net Irrigation (mm)	107		43
Total Labour (h)	126		16
Oct. 15 AM (mm)	44		26
Deep Perc. (mm)	7		4
Total Cost ($/ha)	187		27
Net Returns ($/ha)	-108	(-34.4%)	76

Table 4.34 Irrigated Alfalfa at Edmonton (continued)

EdA9 TCP 30 ha 50%<II<100% (684932)

	mean		SD
Yield (kg/ha)	9595	(5911)	332
CU (mm)	466		31
WUE (kg/ha/mm)	20.6		
Net Irrigation (mm)	163		43
Total Labour (h)	52		16
Oct. 15 AM (mm)	38		26
Deep Perc. (mm)	17		4
Total Cost ($/ha)	450		27
Net Returns ($/ha)	-155	(-34.4%)	76

EdA10 SR2 64 ha 50%<I<100%: 2.0,3.0 (113232)

	mean		SD
Yield (kg/ha)	10104	(6534)	656
CU (mm)	488		34
WUE (kg/ha/mm)	20.7		
Net Irrigation (mm)	250		44
Total Labour (h)	170		15
Oct. 15 AM (mm)	106		31
Deep Perc. (mm)	15		34
Total Cost ($/ha)	319		22
Net Returns ($/ha)	-33	(-10.4%)	54

Table 4.35 Predicted Irrigated Alfalfa Results at Lacombe

LaA1 SCP 65%<I<85% (575757)

	mean		SD
Yield (kg/ha)			
cut 1	6539	(3376)	229
cut 2	5050	(2238)	258
total	11589	(5614)	392
CU (mm)	592		42
WUE (kg/ha/mm)	19.6		
Net Irrigation (mm)	343		43
Total Labour (h)	20		3
Oct. 15 AM (mm)	90		27
Deep Perc. (mm)	8		3
Total Cost ($/ha)	490		35
Net Returns ($/ha)	-13	(-2.7%)	65

LaA2 SCP 65%<I<85% average April 9 AM in irrigated soil=168 mm (575757)

	mean		SD
Yield (kg/ha)	11560	(5614)	351
CU (mm)	604		39
WUE (kg/ha/mm)	19.1		
Net Irrigation (mm)	280		52
Total Labour (h)	21		4
Oct. 15 AM (mm)	98		31
Deep Perc. (mm)	8		3
Total Cost ($/ha)	463		32
Net Returns ($/ha)	13	(2.8%)	67

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA3 TCP 106 ha 65%<I<85% (275638)

	mean		SD
Yield (kg/ha)	10673	(5920)	420
CU (mm)	559		34
WUE (kg/ha/mm)	19.1		
Net Irrigation (mm)	292		34
Total Labour (h)	96		14
Oct. 15 AM (mm)	83		26
Deep Perc. (mm)	7		4
Total Cost ($/ha)	382		25
Net Returns ($/ha)	-1	(-0.4%)	44

LaA4 TCP 106 ha (200 mm) 65%<I<85% (275638)

	mean		SD
Yield (kg/ha)	9843	(5920)	738
CU (mm)	518		41
WUE (kg/ha/mm)	19.0		
Net Irrigation (mm)	200		1
Total Labour (h)	58		11
Oct. 15 AM (mm)	36		27
Deep Perc. (mm)	4		5
Total Cost ($/ha)	333		12
Net Returns ($/ha)	-19	(-5.8%)	29

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA5 TCP 106 ha 50%<I<75% (846437)

	mean		SD
Yield (kg/ha)	9992	(5300)	762
CU (mm)	543		35
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	281		39
Total Labour (h)	96		13
Oct. 15 AM (mm)	93		28
Deep Perc. (mm)	3		1
Total Cost ($/ha)	376		20
Net Returns ($/ha)	-1	(-0.3%)	51

LaA6 TCP 106 ha (200 mm) 35%<I<75% (275638)

	mean		SD
Yield (kg/ha)	9482	(5920)	529
CU (mm)	506		36
WUE (kg/ha/mm)	18.7		
Net Irrigation (mm)	191		18
Total Labour (h)	61		7
Oct. 15 AM (mm)	43		27
Deep Perc. (mm)	1		1
Total Cost ($/ha)	326		20
Net Returns ($/ha)	-41	(-12.6%)	41

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA7 SR2 64 ha 35%<I<85% (575757)

	mean		SD
Yield (kg/ha)	9170	(5614)	611
CU (mm)	502		44
WUE (kg/ha/mm)	18.3		
Net Irrigation (mm)	227		43
Total Labour (h)	146		14
Oct. 15 AM (mm)	82		29
Deep Perc. (mm)	2		1
Total Cost ($/ha)	299		24
Net Returns ($/ha)	-14	(-4.8%)	42

LaA8 SR2 64 ha 50%<I<100% (275638)

	mean		SD
Yield (kg/ha)	9906	(5614)	499
CU (mm)	531		42
WUE (kg/ha/mm)	18.7		
Net Irrigation (mm)	283		45
Total Labour (h)	182		14
Oct. 15 AM (mm)	96		32
Deep Perc. (mm)	10		3
Total Cost ($/ha)	330		27
Net Returns ($/ha)	13	(4.0%)	46

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA9 TCP 45 ha 50%<I<75% (846437)

	mean		SD
Yield (kg/ha)	9094	(5300)	804
CU (mm)	506		38
WUE (kg/ha/mm)	18.0		
Net Irrigation (mm)	229		30
Total Labour (h)	76		7
Oct. 15 AM (mm)	80		27
Deep Perc. (mm)	1		1
Total Cost ($/ha)	375		14
Net Returns ($/ha)	-72	(-19.1%)	35

LaA10 SCP 35%<II<50% (846437)

	mean		SD
Yield (kg/ha)	9590	(5300)	734
CU (mm)	526		32
WUE (kg/ha/mm)	18.2		
Net Irrigation (mm)	233		39
Total Labour (h)	12		2
Oct. 15 AM (mm)	64		25
Deep Perc. (mm)	0		0
Total Cost ($/ha)	427		21
Net Returns ($/ha)	-87	(-20.3%)	60

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA11 SCP 50%<II<85% (575757)

	mean		SD
Yield (kg/ha)			
cut 1	5138	(2940)	264
cut 2	4030	(1955)	300
total	9168	(4894)	414
CU (mm)	483		33
WUE (kg/ha/mm)	19.0		
Net Irrigation (mm)	206		48
Total Labour (h)	14		3
Oct. 15 AM (mm)	28		19
Deep Perc. (mm)	15		4
Total Cost ($/ha)	421		36
Net Returns ($/ha)	-79	(-18.8%)	66

LaA12 SR2 64 ha 50%<III<85% (2,3): 3.0,3.0 (575757)

	mean		SD
Yield (kg/ha)			
cut 1	4496	(3062)	545
cut 2	3436	(2015)	664
total	7932	(5077)	870
CU (mm)	437		45
WUE (kg/ha/mm)	18.2		
Net Irrigation (mm)	132		26
Total Labour (h)	154		15
Oct. 15 AM (mm)	26		17
Deep Perc. (mm)	1		3
Total Cost ($/ha)	250		15
Net Returns ($/ha)	-22	(-8.8%)	45

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA13 SR2 64 ha 50%<III<75%: 3.0,3.0 (575757)

	mean		SD
Yield (kg/ha)			
cut 1	4710	(3062)	517
cut 2	4023	(2015)	403
total	8733	(5077)	577
CU (mm)	480		42
WUE (kg/ha/mm)	18.2		
Net Irrigation (mm)	239		20
Total Labour (h)	172		7
Oct. 15 AM (mm)	54		21
Deep Perc. (mm)	31		16
Total Cost ($/ha)	305		16
Net Returns ($/ha)	-12	(-4.0%)	60

LaA14 SR2 64 ha 75%<III<100%: 3.0,3.0 (483741)

	mean		SD
Yield (kg/ha)	9665	(5392)	524
CU (mm)	506		29
WUE (kg/ha/mm)	19.1		
Net Irrigation (mm)	328		37
Total Labour (h)	212		12
Oct. 15 AM (mm)	84		23
Deep Perc. (mm)	72		14
Total Cost ($/ha)	350		30
Net Returns ($/ha)	-8	(-2.2%)	55

Table 4.35 Irrigated Alfalfa at Lacombe (continued)

LaA15 HHT 64 ha 50%<III<75%: 1.0,2.0 (684932)

	mean		SD
Yield (kg/ha)	9869	(5488)	752
CU (mm)	488		30
WUE (kg/ha/mm)	20.2		
Net Irrigation (mm)	228		42
Total Labour (h)	123		22
Oct. 15 AM (mm)	56		21
Deep Perc. (mm)	4		7
Total Cost ($/ha)	379		25
Net Returns ($/ha)	-29	(-7.7%)	69

LaA16 HHT 48 ha 65%<III<100%: 1.0,2.0 (483741)

	mean		SD
Yield (kg/ha)	10215	(5392)	456
CU (mm)	526		28
WUE (kg/ha/mm)	19.4		
Net Irrigation (mm)	268		39
Total Labour (h)	141		18
Oct. 15 AM (mm)	54		23
Deep Perc. (mm)	23		9
Total Cost ($/ha)	460		31
Net Returns ($/ha)	-75	(-16.3%)	58

Table 4.36 Predicted Irrigated Alfalfa Results at Lethbridge

LeA1 SCP 50%<I<100% (383838)

	mean		SD
Yield (kg/ha)	10444	(3561)	527
CU (mm)	607		46
WUE (kg/ha/mm)	17.2		
Net Irrigation (mm)	352		46
Total Labour (h)	18		2
Oct. 15 AM (mm)	17		14
Deep Perc. (mm)	9		4
Total Cost ($/ha)	510		33
Net Returns ($/ha)	41	(8.0%)	65

LeA2 SCP 65%<I<85% (575757)

	mean		SD
Yield (kg/ha)			
cut 1	6532	(2661)	464
cut 2	5270	(751)	310
total	11804	(3412)	570
CU (mm)	661		56
WUE (kg/ha/mm)	17.9		
Net Irrigation (mm)	389		15
Total Labour (h)	22		1
Oct. 15 AM (mm)	12		12
Deep Perc. (mm)	5		2
Total Cost ($/ha)	539		23
Net Returns ($/ha)	132	(24.5%)	53

Table 4.36 Irrigated Alfalfa at Lethbridge (continued)

LeA3 SCP 75%<I<100% (383838)

	mean		SD
Yield (kg/ha)	12184	(3561)	571
CU (mm)	693		47
WUE (kg/ha/mm)	17.6		
Net Irrigation (mm)	459		30
Total Labour (h)	26		2
Oct. 15 AM (mm)	25		20
Deep Perc. (mm)	20		7
Total Cost ($/ha)	582		34
Net Returns ($/ha)	118	(20.3%)	71

LeA4 SCP 25%<I<100% (383838)

	mean		SD
Yield (kg/ha)	9160	(3561)	796
CU (mm)	543		45
WUE (kg/ha/mm)	16.9		
Net Irrigation (mm)	280		48
Total Labour (h)	15		3
Oct. 15 AM (mm)	14		14
Deep Perc. (mm)	4		4
Total Cost ($/ha)	467		36
Net Returns ($/ha)	-19	(-4.1%)	69

Table 4.36 Irrigated Alfalfa at Lethbridge (continued)

LeA5 SCP 50%<II<85% (575757)

	mean		SD
Yield (kg/ha)	8956	(2907)	659
CU (mm)	487		46
WUE (kg/ha/mm)	18.4		
Net Irrigation (mm)	241		31
Total Labour (h)	17		2
Oct. 15 AM (mm)	7		9
Deep Perc. (mm)	12		2
Total Cost ($/ha)	454		24
Net Returns ($/ha)	30	(6.6%)	44

LeA6 SCP 65%<III<100% (846437)

	mean		SD
Yield (kg/ha)			
cut 1	6480	(2815)	264
cut 2	4725	(571)	252
total	11206	(3386)	428
CU (mm)	623		33
WUE (kg/ha/mm)	18.0		
Net Irrigation (mm)	358		49
Total Labour (h)	27		4
Oct. 15 AM (mm)	4		6
Deep Perc. (mm)	14		16
Total Cost ($/ha)	521		33
Net Returns ($/ha)	105	(20.2%)	86

Table 4.36 Irrigated Alfalfa at Lethbridge (continued)

LeA7 SR2 32 ha 50%<I<85%: 3.0,3.0 (275638)

	mean		SD
Yield (kg/ha)	9766	(3688)	513
CU (mm)	600		40
WUE (kg/ha/mm)	16.3		
Net Irrigation (mm)	330		46
Total Labour (h)	112		8
Oct. 15 AM (mm)	16		13
Deep Perc. (mm)	10		3
Total Cost ($/ha)	466		28
Net Returns ($/ha)	31	(6.7%)	51

LeA8 SR2 32 ha 65%<I<100%: 3.0,3.0 (234756)

	mean		SD
Yield (kg/ha)	10018	(3518)	626
CU (mm)	632		50
WUE (kg/ha/mm)	15.9		
Net Irrigation (mm)	361		39
Total Labour (h)	122		7
Oct. 15 AM (mm)	19		12
Deep Perc. (mm)	18		7
Total Cost ($/ha)	482		24
Net Returns ($/ha)	39	(8.0%)	82

Table 4.36 Irrigated Alfalfa at Lethbridge (continued)

LeA9 SR2 67.3 ha 50%<I<100%: 3.0,3.0 (383838)

	mean		SD
Yield (kg/ha)			
cut 1	4965	(2899)	707
cut 2	4100	(662)	269
total	9065	(3561)	756
CU (mm)	562		44
WUE (kg/ha/mm)	16.1		
Net Irrigation (mm)	307		32
Total Labour (h)	198		10
Oct. 15 AM (mm)	20		18
Deep Perc. (mm)	6		4
Total Cost ($/ha)	352		28
Net Returns ($/ha)	88	(25.0%)	55

LeA10 SR2 64 ha 50%<I<100% (1,2): 3.0,3.0 irrigation during May allowed (846437)

	mean		SD
Yield (kg/ha)			
cut 1	5638	(3043)	456
cut 2	2346	(851)	547
total	7985	(3895)	796
CU (mm)	497		46
WUE (kg/ha/mm)	16.1		
Net Irrigation (mm)	198		33
Total Labour (h)	128		11
Oct. 15 AM (mm)	4		4
Deep Perc. (mm)	6		4
Total Cost ($/ha)	358		22
Net Returns ($/ha)	29	(8.1%)	55

Table 4.36 Irrigated Alfalfa at Lethbridge (continued)

LeA11 SR1 50.4 ha 50%<I<100%: 3.0,3.0 (383838)

	mean		SD
Yield (kg/ha)	7584	(3561)	814
CU (mm)	488		47
WUE (kg/ha/mm)	15.5		
Net Irrigation (mm)	223		26
Total Labour (h)	106		12
Oct. 15 AM (mm)	13		12
Deep Perc. (mm)	1		1
Total Cost ($/ha)	300		27
Net Returns ($/ha)	22	(7.3%)	53

LeA12 SR2 32 ha 50%<100%: 3.0,3.0 irrigation after second cut until September 1 (838383)

	mean		SD
Yield (kg/ha)	9780	(3848)	403
CU (mm)	677		41
WUE (kg/ha/mm)	14.4		
Net Irrigation (mm)	447		48
Total Labour (h)	152		7
Oct. 15 AM (mm)	67		27
Deep Perc. (mm)	16		5
Total Cost ($/ha)	551		23
Net Returns ($/ha)	-77	(-13.9%)	58

4.4.2 Model Results for Wheat

Unlike alfalfa, the model predicted that the Black soil zone has more variation in dryland wheat yields than the Dark Brown soil zone. The reasons for this was that killing frosts were predicted to occur more frequently at Edmonton and Lacombe and, as well, wheat grown at these locations had more variation in moisture conditions than at Coronation or Lethbridge. In some years at Edmonton and Lacombe dryland wheat underwent almost no moisture stress while in other years moisture stress was as severe as in the Dark Brown soil zone. By comparison, the dryland wheat at Coronation and Lethbridge was always subjected to some moisture stress. Table 4.37 gives the predicted results for dryland wheat at all locations studied.

The predicted October 15 AM in dryland soils for wheat was greater at all locations than for alfalfa. Predicted dryland deep percolation was relatively small and, as for alfalfa, was greatest on the soil with the worst internal drainage -- soil type II.

In east central Alberta, Coronation is the most attractive location to irrigate wheat because it is the driest location. Table 4.38 presents predicted irrigated wheat results for many model runs at Coronation. Runs CoW1 to CoW12 all involved irrigation with a stationary centre pivot. For run CoW2 the irrigated soil always started out at field capacity on April 9. This represents an average

Table 4.37 Predicted Dryland Wheat Results

	Soil Type					
	I		II		III	
Loc. result	mean	SD	mean	SD	mean	SD
Cor. (seed number)	(575757)		(838383)		(846437)	
Yield (kg/ha)	1850	368	1549	436	1587	377
CU (mm)	232	36	202	39	205	35
WUE (kg/ha/mm)	7.97		7.67		7.74	
Oct. 15 AM (mm)	23	16	26	15	17	16
Deep Perc. (mm)	0	0	3	3	0	0
Edm. (seed number)	(846437)		(846437)		(846437)	
Yield (kg/ha)	2580	526	2272	513	2097	551
CU (mm)	305	42	255	41	269	44
WUE (kg/ha/mm)	8.46		8.91		8.17	
Oct. 15 AM (mm)	49	28	44	25	40	20
Deep Perc. (mm)	2	9	6	6	3	3
Lac. (seed number)	(846437)		(846437)		(846437)	
Yield (kg/ha)	2098	698	1923	658	1867	690
CU (mm)	288	60	267	56	264	59
WUE (kg/ha/mm)	7.28		7.20		7.07	
Oct. 15 AM (mm)	34	21	40	22	35	21
Deep Perc. (mm)	0	0	7	4	1	3
Leth. (seed number)	(383838)		(365455)		(365455)	
Yield (kg/ha)	1648	412	1416	420	1452	400
CU (mm)	241	43	202	44	210	42
WUE (kg/ha/mm)	6.84		7.01		6.91	
Oct. 15 AM (mm)	17	10	15	12	11	12
Deep Perc. (mm)	0	1	3	3	3	8

of 49 mm more moisture on April 9 than assumed for the other model runs. The net irrigation requirement was reduced by approximately this depth of water. Given the variable costs of applying water ($0.4335/mm), the reduced irrigation requirement was worth about $18/ha. This was the amount that average annual net returns were increased. As for alfalfa, any additional soil moisture in the irrigated soil in the spring will reduce net irrigation needs by the amount of the extra moisture and increase annual net returns by the value of lowered variable irrigation costs. Invariably, the irrigated soils were predicted to contain more fall moisture than the adjacent dryland soils. If all the moisture difference between dryland and irrigated soils were carried forward into the next year then the effect on irrigation needs and on annual net returns will be approximately as described above.

Runs CoW3, CoW4, and CoW5 demonstrate the impact of allowable AM depletion on yields and returns. Permitting greater than 50% AM depletion markedly reduced both yields and returns (CoW3 versus CoW1, CoW4, or CoW5).

The model predicted that irrigation during the crop establishment period slightly decreased net returns. This practice maintained the entire soil profile continually moist so that a large amount of moisture was lost as deep percolation. Because the lower portion of the root zone was moist, the reserve of available soil moisture was larger than if irrigation was delayed until the pre-jointing stage. Consequently, with early irrigation, less irrigation was necessary during other growth stages when crop moisture needs were greatest. Thus the upper part of the soil tended to be drier. The assumed root distribution (i.e. the VSMB k coefficients) predict most of the moisture used by the plants is extracted from the upper one-half of the root zone. As a result, early irrigation tended to reduce ET during the growth stages when crop yield was most sensitive to moisture stress.

For runs CoW7 and CoW8, the irrigation scheduling criteria were applied only to the upper 50% of the root zone. The scheduling criteria tended to produce frequent, relatively light applications. This practice made very efficient use of irrigation water because deep percolation and October 15 AM were minimized. Keeping the upper half of the root zone near field capacity (run CoW8) may be the most economical way to manage irrigation with a SCP.

Examination of the Wageningen wheat yield model indicates the crop should be most sensitive to improved moisture conditions during the flowering stage. This growth stage is encompassed within irrigation scheduling crop growth stage 4. Run CoW9 shows that decreasing allowable AM depletion during irrigation scheduling period 4 results in significant improvement in yield and net returns (CoW9 versus CoW3). Run CoW10 indicates allowing greater AM depletion during the pre-soft dough to hard dough stage (irrigation scheduling crop growth stage 5) is marginally better economically than providing full irrigation during this last stage (CoW10 versus CoW1). Allowing greater AM depletion during the latter stage permits the crop to make best use of available soil moisture already stored in the soil profile.

A severly limited irrigation water supply had a pronounced detrimental effect on irrigated yields and returns. For runs CoW11 and CoW12 there was sufficient water for about one irrigation. Irrigation was very unprofitable although it did raise average yields 25% and reduce the variability in yields compared with dryland yields. With a severely restricted seasonal water supply there was a marginal benefit in delaying irrigation until a few days before the heading stage.

Runs CoW13 to CoW16 involved a 400 m long TCP irrigating two circles. Maintaining less than 35% AM depletion was optimal. With the above depletion level there was very little detrimental effect when the irrigation season was shortened by one or two weeks (CoW16 versus CoW15). However, such a practice can significantly lessen the amount of physical labour needed.

With a moderate restriction in seasonal water supply, there was no advantage to delaying irrigation until just before the heading stage (runs CoW17 and CoW18). Again, the limited water supply made irrigation very unprofitable.

Runs CoW19 to CoW23 investigate the effect of different management strategies with a two lateral side roll system irrigating 64 ha. Allowing irrigation sets which apply more than 50% of root zone AM capacity (run CoW19) was less profitable than restricting each application to 50% of root zone AM capacity (run CoW20). This was because the longer set times delay system movement through the field. Consequently the last part of the field to be irrigated became undesirably dry. However, using shorter set times necessitated about 50% more physical labour to move the system. Using eight hour sets (which apply 50% of AM root zone capacity), the most profitable scheduling criteria was to try to maintain less than 35% AM depletion. As explained for alfalfa, this particular irrigation system could not, in fact, keep soil for the entire irrigated area at less than 35% AM depletion.

Neither the one lateral side roll (run CoW24) or the HHT (run CoW25) were predicted to be profitable. Both systems require a large amount of manual labour compared with expected net returns. Irrigating three circles with the 400 m long TCP was predicted to be more profitable than irrigating just two circles (run CoW26 versus CoW14). The model predicts irrigating three circles required an average of about one extra move of the pivot over the irrigation season.

For a stationary pivot, the predicted simple rate of return was about the same for soil type II and for soil type I (run CoW29 versus CoW1). However, for a towable pivot, net returns were predicted to be lower on soil type II relative to soil type I (run CoW28 versus CoW14). This was expected since soil type II becomes drier between irrigations. Permitting large AM depletion was particularly undesirable for soil type II (run CoW27). For soil type III, net returns from irrigation with a SCP was about the same as with soil type I. Although irrigated soil types II and III were predicted to contain more AM than dryland soils on October 15, the difference was not as large as predicted for soil type I. Hence, the effect of fall stored soil moisture on irrigation and returns in the next year would not be as great as for soil type I.

Carrying forward all the additional soil moisture on October 15 in the irrigated soils into the next year shows that the 400 m long TCP and the two lateral side roll irrigating 64 ha would both have positive net returns (providing irrigation is started as soon a possible after AM becomes more than 35% depleted). However, the simple rates of returns are not especially attractive. Including the effect of hail and potential marketing problems, irrigation of wheat at Coronation appears to be a marginal investment. Even with a very well managed irrigation system, the improved yields from irrigation could just pay for the costs of irrigation. There was little predicted returns for the time the farmer spent scheduling irrigation and repairing and maintaining the irrigation system.

Dryland wheat farming with crop insurance which provides for coverage for yield losses due to drought would probably be more profitable than irrigation farming of wheat at Coronation.

Weather at Edmonton usually produced very good yields of dryland wheat at Edmonton. In fact about one year out of 25, virtually no irrigation was predicted to be needed even allowing as little as 50% AM depletion. Consequently, net returns at Edmonton for irrigating wheat were always negative. Table 4.39 lists model results for irrigated wheat at Edmonton. Even after making approximate allowances for carrying forward October 15 AM, none of the irrigation systems or practices listed in Table 4.39 were near being profitable. The model results strongly suggest that irrigating wheat in the Edmonton area is not a worthwhile undertaking.

The timing and amount of precipitation at Lacombe is not as favourable for dryland wheat as it is at Edmonton. Therefore, irrigating wheat at Lacombe was more profitable than at Edmonton. Table 4.40 presents model results for irrigated wheat at Lacombe. Unlike the other locations studied, the standard deviation of the irrigated wheat was greater than the standard deviation of dryland wheat. This was because killing frosts caused greater numerical variation in irrigated wheat production than in dryland wheat production.

With a SCP, shortening the irrigation season by one or two weeks was more profitable than continuing irrigation after the soft dough stage has been reached (run LaW2 versus LaW1). This practice improved the efficiency with which irrigation water was used.

Run LaW3 involves an overextended HHT irrigating at 75% AM depletion. This system represents a system which would be set up and used only about two years out of three. The system significantly increased yields in dry years but overall did not improve net returns or decrease yield variability relative to dryland farming. Run LaW4 uses the same irrigation system but requires some irrigation every year. Although net returns were larger, the economics were still unfavourable.

Neither the two lateral side roll (run LaW7) nor the 400 m long TCP irrigating two circles were profitable. The latter system almost had positive average annual net returns if all the additional AM in the irrigated soil on October 15 were carried forward into the next season (average annual net returns would become about -$9/ha). Irrigating soil types II and III at Lacombe had approximately the same annual net returns as irrigating soil type I (runs LaW7 and LaW8).

Lacombe lies in an area of Alberta particularly prone to damaging hail. This combined with the risk of frost and the generally poor predicted net returns suggests irrigating wheat in the Lacombe district is not economically feasible.

The greatest potential yield increases for irrigated wheat over dryland wheat were at Lethbridge. Table 4.41 lists model results for irrigated wheat at Lethbridge. With a SCP, maximum predicted profits occurred when irrigation was started before the soil became more than one-half depleted of AM (run LeW3 versus LeW2 and LeW3). Assuming all the additional AM present in the irrigated soil on October 15 were carried over into the next year for run LeW3, irrigation requirements would be reduced by about 50 mm and annual net returns increased by $22/ha.

None of the three overextended side rolls at Lethbridge were profitable (runs LeW4, LeW5, and LeW6). The side roll most capable of supplying crop moisture needs (the two lateral side roll irrigating 67.2 ha) also had the largest net returns of the three systems. However, even after making an approximate allowance for the effect of carrying forward fall stored soil moisture, this system would not produce average net returns larger than zero.

The predicted yield increase over dryland yield was less for soil types II and III than for soil type I (runs LeW7 and LeW8 versus run LeW3). Because of the relatively large consumptive use rates at Lethbridge, soil types II and III can quickly become undesirably dry. Consequently, the problem of having poorer net returns for soil type II and III relative to soil type I would probably be more pronounced with intermittent move irrigation systems which force the crop to rely partly on the available soil moisture stored between irrigations.

The model results indicate that irrigation of hard wheat at Lethbridge was considerably less profitable than irrigating perennial forages, such as alfalfa hay. Irrigating hard wheat has generally been found to be, at best, only marginally profitable in southern Alberta (ECA 1982). Therefore, the model results are consistent with the known performance.

Table 4.38 Predicted Irrigated Wheat Results at Coronation

CoW1 SCP 65%<I<85% (575757)

	mean		SD
Yield (kg/ha)	3760	(1850)	142
CU (mm)	396		14
WUE (kg/ha/mm)	9.49		
Net Irrigation (mm)	251		27
Total Labour (h)	15		2
Oct. 15 AM (mm)	93		17
Deep Perc. (mm)	7		3
Total Cost ($/ha)	418		16
Net Returns ($/ha)	-64	(-16.3%)	55

CoW2 SCP 65%<I<85% April 9 AM for irrigated soil=144 mm (575757)

	mean		SD
Yield (kg/ha)	3798	(1850)	177
CU (mm)	407		19
WUE (kg/ha/mm)	9.33		
Net Irrigation (mm)	209		29
Total Labour (h)	16		2
Oct. 15 AM (mm)	93		16
Deep Perc. (mm)	7		6
Total Cost ($/ha)	399		17
Net Returns ($/ha)	-47	(-11.8%)	55

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW3 SCP 35%<I<75% (575757)

	mean		SD
Yield (kg/ha)	3045	(1850)	262
CU (mm)	338		21
WUE (kg/ha/mm)	9.01		
Net Irrigation (mm)	159		31
Total Labour (h)	9		2
Oct. 15 AM (mm)	65		15
Deep Perc. (mm)	1		1
Total Cost ($/ha)	368		13
Net Returns ($/ha)	-147	(-40.0%)	40

CoW4 SCP 75%<I<100% (575757)

	mean		SD
Yield (kg/ha)	3910	(1850)	128
CU (mm)	412		16
WUE (kg/ha/mm)	9.49		
Net Irrigation (mm)	291		32
Total Labour (h)	22		3
Oct. 15 AM (mm)	114		15
Deep Perc. (mm)	18		7
Total Cost ($/ha)	437		18
Net Returns ($/ha)	-55	(-12.6%)	56

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW5 SCP 50%<I<75% (575757)

	mean		SD
Yield (kg/ha)	3557	(1850)	159
CU (mm)	379		21
WUE (kg/ha/mm)	9.39		
Net Irrigation (mm)	208		31
Total Labour (h)	16		2
Oct. 15 AM (mm)	78		19
Deep Perc. (mm)	2		2
Total Cost ($/ha)	396		17
Net Returns ($/ha)	-80	(-20.3%)	53

CoW6 SCP 50%<I<85% (1,2,3,4,5) irrigation during May allowed (575757)

	mean		SD
Yield (kg/ha)	3246	(1850)	255
CU (mm)	394		23
WUE (kg/ha/mm)	8.24		
Net Irrigation (mm)	274		32
Total Labour (h)	21		3
Oct. 15 AM (mm)	86		16
Deep Perc. (mm)	46		16
Total Cost ($/ha)	420		17
Net Returns ($/ha)	-162	(-38.6%)	48

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW7 SCP 50%<I<100% upper 50% of root zone only (575757)

	mean		SD
Yield (kg/ha)	3458	(1850)	165
CU (mm)	368		19
WUE (kg/ha/mm)	9.40		
Net Irrigation (mm)	190		24
Total Labour (h)	11		1
Oct. 15 AM (mm)	64		17
Deep Perc. (mm)	1		2
Total Cost ($/ha)	387		16
Net Returns ($/ha)	-90	(-23.3%)	59

CoW8 SCP 75%<I<100% upper 50% of root zone only (575757)

	mean		SD
Yield (kg/ha)	3871	(1850)	150
CU (mm)	406		19
WUE (kg/ha/mm)	9.53		
Net Irrigation (mm)	244		24
Total Labour (h)	20		2
Oct. 15 AM (mm)	79		18
Deep Perc. (mm)	3		2
Total Cost ($/ha)	416		18
Net Returns ($/ha)	-42	(-10.1%)	63

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW9 SCP 35%<I<65% (3,5) 65%<I<85% (4) (575757)

	mean		SD
Yield (kg/ha)	3496	(1850)	163
CU (mm)	368		18
WUE (kg/ha/mm)	9.50		
Net Irrigation (mm)	191		33
Total Labour (h)	16		3
Oct. 15 AM (mm)	74		18
Deep Perc. (mm)	3		2
Total Cost ($/ha)	387		18
Net Returns ($/ha)	-83	(-21.4%)	51

CoW10 SCP 65%<I<85% (3,4) 35%<I<85% (5) (575757)

	mean		SD
Yield (kg/ha)	3683	(1850)	172
CU (mm)	385		21
WUE (kg/ha/mm)	9.57		
Net Irrigation (mm)	208		33
Total Labour (h)	16		3
Oct. 15 AM (mm)	73		17
Deep Perc. (mm)	4		1
Total Cost ($/ha)	397		18
Net Returns ($/ha)	-58	(-14.6%)	51

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW11 SCP (50 mm) 50%<I<85% (365455)

	mean		SD
Yield (kg/ha)	2606	(2044)	323
CU (mm)	293		30
WUE (kg/ha/mm)	8.89		
Net Irrigation (mm)	48		3
Total Labour (h)	3		0
Oct. 15 AM (mm)	25		13
Deep Perc. (mm)	1		1
Total Cost ($/ha)	311		6
Net Returns ($/ha)	-207	(-66.6%)	28

CoW12 SCP (50 mm) 50%<I<85% (4,5) (365455)

	mean		SD
Yield (kg/ha)	2643	(2044)	330
CU (mm)	291		31
WUE (kg/ha/mm)	9.08		
Net Irrigation (mm)	50		0
Total Labour (h)	3		0
Oct. 15 AM (mm)	30		14
Deep Perc. (mm)	0		0
Total Cost ($/ha)	312		6
Net Returns ($/ha)	-201	(-64.4%)	31

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW13 TCP 106 ha 35%<I<65% (575757)

	mean		SD
Yield (kg/ha)	2994	(1850)	220
CU (mm)	332		17
WUE (kg/ha/mm)	9.02		
Net Irrigation (mm)	148		28
Total Labour (h)	78		16
Oct. 15 AM (mm)	60		19
Deep Perc. (mm)	1		1
Total Cost ($/ha)	285		14
Net Returns ($/ha)	-73	(-25.6%)	40

CoW14 TCP 106 ha 50%<I<85% (575757)

	mean		SD
Yield (kg/ha)	3297	(1850)	188
CU (mm)	358		20
WUE (kg/ha/mm)	9.20		
Net Irrigation (mm)	188		29
Total Labour (h)	88		13
Oct. 15 AM (mm)	80		18
Deep Perc. (mm)	3		5
Total Cost ($/ha)	305		16
Net Returns ($/ha)	-37	(-12.1%)	46

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW15 TCP 106 ha 65%<I<85% (575757)

	mean		SD
Yield (kg/ha)	3447	(1850)	168
CU (mm)	368		18
WUE (kg/ha/mm)	9.37		
Net Irrigation (mm)	214		20
Total Labour (h)	98		14
Oct. 15 AM (mm)	87		16
Deep Perc. (mm)	4		2
Total Cost ($/ha)	321		12
Net Returns ($/ha)	-25	(-7.8%)	51

CoW16 TCP 106 ha 65%<I<85% (3,4) (575757)

	mean		SD
Yield (kg/ha)	3293	(1850)	205
CU (mm)	353		22
WUE (kg/ha/mm)	9.33		
Net Irrigation (mm)	169		23
Total Labour (h)	72		11
Oct. 15 AM (mm)	68		18
Deep Perc. (mm)	3		1
Total Cost ($/ha)	298		13
Net Returns ($/ha)	-31	(-10.4%)	47

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW17 TCP 106 ha (100 mm) 65%<I<85% (575757)

	mean		SD
Yield (kg/ha)	2798	(1850)	332
CU (mm)	311		28
WUE (kg/ha/mm)	9.00		
Net Irrigation (mm)	100		1
Total Labour (h)	40		12
Oct. 15 AM (mm)	36		14
Deep Perc. (mm)	1		1
Total Cost ($/ha)	261		10
Net Returns ($/ha)	-85	(-32.6%)	51

CoW18 TCP 106 ha (100 mm) 65%<I<85% (4,5) (575757)

	mean		SD
Yield (kg/ha)	2678	(1850)	336
CU (mm)	300		33
WUE (kg/ha/mm)	8.93		
Net Irrigation (mm)	100		1
Total Labour (h)	28		6
Oct. 15 AM (mm)	54		18
Deep Perc. (mm)	1		1
Total Cost ($/ha)	258		3
Net Returns ($/ha)	-105	(-40.7%)	42

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW19 SR2 64 ha 50%<I<100%: 2.0,3.0 (575757)

	mean		SD
Yield (kg/ha)	2892	(1850)	279
CU (mm)	324		25
WUE (kg/ha/mm)	8.93		
Net Irrigation (mm)	195		43
Total Labour (h)	100		11
Oct. 15 AM (mm)	106		19
Deep Perc. (mm)	19		5
Total Cost ($/ha)	321		21
Net Returns ($/ha)	-68	(-21.2%)	44

CoW20 SR2 64 ha 50%<I<100%: 3.0,3.0 (575757)

	mean		SD
Yield (kg/ha)	3043	(1850)	246
CU (mm)	337		22
WUE (kg/ha/mm)	9.03		
Net Irrigation (mm)	185		31
Total Labour (h)	144		13
Oct. 15 AM (mm)	92		17
Deep Perc. (mm)	8		4
Total Cost ($/ha)	258		16
Net Returns ($/ha)	-45	(-17.4%)	40

Table 4.38 Irrigated Wheat at Cornonation (continued)

CoW21 SR2 64 ha 75%<I<100%: 3.0,3.0 (575757)

	mean		SD
Yield (kg/ha)	3286	(1850)	192
CU (mm)	355		38
WUE (kg/ha/mm)	9.26		
Net Irrigation (mm)	252		29
Total Labour (h)	205		12
Oct. 15 AM (mm)	120		16
Deep Perc. (mm)	28		5
Total Cost ($/ha)	291		30
Net Returns ($/ha)	-33	(-11.3%)	46

CoW22 SR2 64 ha 35%<I<85%: 3.0,3.0 (575757)

	mean		SD
Yield (kg/ha)	2842	(1850)	251
CU (mm)	321		23
WUE (kg/ha/mm)	8.85		
Net Irrigation (mm)	142		22
Total Labour (h)	118		9
Oct. 15 AM (mm)	71		16
Deep Perc. (mm)	2		2
Total Cost ($/ha)	236		24
Net Returns ($/ha)	-60	(-25.4%)	40

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW23 SR2 64 ha 65%<I<85%: 3.0,3.0 (575757)

	mean		SD
Yield (kg/ha)	3212	(1850)	209
CU (mm)	348		19
WUE (kg/ha/mm)	9.23		
Net Irrigation (mm)	235		24
Total Labour (h)	196		10
Oct. 15 AM (mm)	108		16
Deep Perc. (mm)	22		4
Total Cost ($/ha)	283		12
Net Returns ($/ha)	-31	(-11.0%)	41

CoW24 SR1 48 ha 65%<I<85%: 3.0,3.0 (757575)

	mean		SD
Yield (kg/ha)	3062	(1915)	234
CU (mm)	335		20
WUE (kg/ha/mm)	9.14		
Net Irrigation (mm)	186		21
Total Labour (h)	110		13
Oct. 15 AM (mm)	103		18
Deep Perc. (mm)	18		13
Total Cost ($/ha)	256		12
Net Returns ($/ha)	-44	(-17.2%)	32

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW25 HHT 64 ha 35%<I<85%: 1.0,2.0 (684932)

	mean		SD
Yield (kg/ha)	2703	(1903)	281
CU (mm)	304		27
WUE (kg/ha/mm)	8.89		
Net Irrigation (mm)	97		15
Total Labour (h)	115		18
Oct. 15 AM (mm)	42		18
Deep Perc. (mm)	0		0
Total Cost ($/ha)	262		8
Net Returns ($/ha)	-144	(-43.5%)	39

CoW26 TCP 159 ha 50%<I<65% (575757)

	mean		SD
Yield (kg/ha)	3095	(1850)	221
CU (mm)	339		21
WUE (kg/ha/mm)	9.13		
Net Irrigation (mm)	174		22
Total Labour (h)	98		11
Oct. 15 AM (mm)	77		17
Deep Perc. (mm)	3		2
Total Cost ($/ha)	241		10
Net Returns ($/ha)	-11	(-4.6%)	43

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW27 SCP 25%<II<85% (838383)

	mean		SD
Yield (kg/ha)	2515	(1549)	210
CU (mm)	285		19
WUE (kg/ha/mm)	8.82		
Net Irrigation (mm)	107		35
Total Labour (h)	7		2
Oct. 15 AM (mm)	45		14
Deep Perc. (mm)	8		3
Total Cost ($/ha)	342		18
Net Returns ($/ha)	-163	(-47.7%)	44

CoW28 TCP 106 ha 50%<II<100% (113232)

	mean		SD
Yield (kg/ha)	2783	(1540)	178
CU (mm)	312		12
WUE (kg/ha/mm)	8.92		
Net Irrigation (mm)	146		41
Total Labour (h)	54		17
Oct. 15 AM (mm)	54		18
Deep Perc. (mm)	13		3
Total Cost ($/ha)	285		10
Net Returns ($/ha)	-55	(-19.4%)	61

Table 4.38 Irrigated Wheat at Coronation (continued)

CoW29 SCP 65%<II<85% (838383)

	mean		SD
Yield (kg/ha)	3288	(1549)	139
CU (mm)	347		15
WUE (kg/ha/mm)	9.48		
Net Irrigation (mm)	197		46
Total Labour (h)	12		3
Oct. 15 AM (mm)	62		16
Deep Perc. (mm)	19		4
Total Cost ($/ha)	402		24
Net Returns ($/ha)	-70	(-17.4%)	60

CoW30 SCP 65%<III<85% (846437)

	mean		SD
Yield (kg/ha)	3476	(1587)	163
CU (mm)	363		20
WUE (kg/ha/mm)	9.58		
Net Irrigation (mm)	217		27
Total Labour (h)	11		1
Oct. 15 AM (mm)	58		12
Deep Perc. (mm)	14		10
Total Cost ($/ha)	403		14
Net Returns ($/ha)	-53	(-13.2%)	55

Table 4.39 Predicted Irrigated Wheat Results at Edmonton

EdW1 SCP 65%<I<85% (846437)

	mean		SD
Yield (kg/ha)	3936	(2580)	122
CU (mm)	416		17
WUE (kg/ha/mm)	9.46		
Net Irrigation (mm)	190		54
Total Labour (h)	15		5
Oct. 15 AM (mm)	115		17
Deep Perc. (mm)	16		18
Total Cost ($/ha)	369		31
Net Returns ($/ha)	-119	(-32.2%)	73

EdW2 SCP 65%<I<85% average April 9 AM for irrigated soils=144 mm (846437)

	mean		SD
Yield (kg/ha)	3914	(2580)	134
CU (mm)	418		15
WUE (kg/ha/mm)	9.36		
Net Irrigation (mm)	150		49
Total Labour (h)	12		4
Oct. 15 AM (mm)	114		18
Deep Perc. (mm)	15		16
Total Cost ($/ha)	352		29
Net Returns ($/ha)	-106	(-30.1%)	74

Table 4.39 Irrigated Wheat at Edmonton (continued)

EdW3 SCP 65%<II<85% (846437)

	mean		SD
Yield (kg/ha)	3410	(2272)	203
CU (mm)	364		17
WUE (kg/ha/mm)	9.37		
Net Irrigation (mm)	137		52
Total Labour (h)	7		3
Oct. 15 AM (mm)	78		21
Deep Perc. (mm)	21		5
Total Cost ($/ha)	352		26
Net Returns ($/ha)	-144	(-40.9%)	83

EdW4 SCP 50%<III<75% (846437)

	mean		SD
Yield (kg/ha)	3349	(2197)	224
CU (mm)	351		19
WUE (kg/ha/mm)	9.32		
Net Irrigation (mm)	122		40
Total Labour (h)	6		2
Oct. 15 AM (mm)	59		16
Deep Perc. (mm)	18		24
Total Cost ($/ha)	338		20
Net Returns ($/ha)	-125	(-37.0%)	69

Table 4.39 Irrigated Wheat at Edmonton (continued)

EdW5 SR2 64 ha 50%<I<100%: 2.0,3.0 (113232)

	mean		SD
Yield (kg/ha)	3360	(2542)	720
CU (mm)	336		19
WUE (kg/ha/mm)	9.18		
Net Irrigation (mm)	141		34
Total Labour (h)	129		16
Oct. 15 AM (mm)	94		23
Deep Perc. (mm)	13		13
Total Cost ($/ha)	220		18
Net Returns ($/ha)	-69	(-31.4%)	60

EdW6 TCP 45 ha 50%<I<85% (113232)

	mean		SD
Yield (kg/ha)	3371	(2542)	725
CU (mm)	367		18
WUE (kg/ha/mm)	9.19		
Net Irrigation (mm)	136		39
Total Labour (h)	46		14
Oct. 15 AM (mm)	91		20
Deep Perc. (mm)	10		8
Total Cost ($/ha)	291		20
Net Returns ($/ha)	-138	(-47.4%)	62

Table 4.40 Predicted Irrigated Wheat Results at Lacombe

LaW1 SCP 50%<I<75% (846437)

	mean		SD
Yield (kg/ha)	3494	(2098)	1063
CU (mm)	419		61
WUE (kg/ha/mm)	8.34		
Net Irrigation (mm)	181		63
Total Labour (h)	14		5
Oct. 15 AM (mm)	94		21
Deep Perc. (mm)	3		4
Total Cost ($/ha)	366		36
Net Returns ($/ha)	-107	(-29.2%)	94

LaW2 SCP 50%<I<75% (3,4) (846437)

	mean		SD
Yield (kg/ha)	3531	(2098)	764
CU (mm)	405		61
WUE (kg/ha/mm)	8.72		
Net Irrigation (mm)	154		59
Total Labour (h)	8		3
Oct. 15 AM (mm)	73		23
Deep Perc. (mm)	3		2
Total Cost ($/ha)	355		28
Net Returns ($/ha)	-90	(-25.4%)	83

Table 4.40 Irrigated Wheat at Lacombe (continued)

LaW3 HHT 64 ha 25%<I<75%: 1.0,2.0 (846437)

	mean		SD
Yield (kg/ha)	2526	(2098)	826
CU (mm)	338		50
WUE (kg/ha/mm)	7.47		
Net Irrigation (mm)	76		42
Total Labour (h)	60		33
Oct. 15 AM (mm)	72		26
Deep Perc. (mm)	2		2
Total Cost ($/ha)	230		22
Net Returns ($/ha)	-150	(-65.5%)	45

LaW4 HHT 64 ha 50%<I<100%: 1.0,2.0 (113232)

	mean		SD
Yield (kg/ha)	3061	(2024)	1170
CU (mm)	380		65
WUE (kg/ha/mm)	8.06		
Net Irrigation (mm)	169		45
Total Labour (h)	90		24
Oct. 15 AM (mm)	89		10
Deep Perc. (mm)	9		10
Total Cost ($/ha)	297		22
Net Returns ($/ha)	-105	(-35.4%)	73

Table 4.40 Irrigated Wheat at Lacombe (continued)

LaW5 SR2 64 ha 50%<I<100%: 3.0,3.0 (234756)

	mean		SD
Yield (kg/ha)	3095	(2161)	962
CU (mm)	388		67
WUE (kg/ha/mm)	7.97		
Net Irrigation (mm)	171		45
Total Labour (h)	142		19
Oct. 15 AM (mm)	106		19
Deep Perc. (mm)	15		8
Total Cost ($/ha)	235		20
Net Returns ($/ha)	-62	(-26.4%)	50

LaW6 TCP 106 ha 50%<I<75% (483741)

	mean		SD
Yield (kg/ha)	3464	(2098)	745
CU (mm)	404		61
WUE (kg/ha/mm)	8.80		
Net Irrigation (mm)	175		57
Total Labour (h)	76		27
Oct. 15 AM (mm)	93		21
Deep Perc. (mm)	4		3
Total Cost ($/ha)	286		27
Net Returns ($/ha)	-33	(-11.5%)	72

Table 4.40 Irrigated Wheat at Lacombe (continued)

LaW7 SCP 65%<II<100% (846437)

	mean		SD
Yield (kg/ha)	3370	(1923)	733
CU (mm)	386		60
WUE (kg/ha/mm)	8.73		
Net Irrigation (mm)	164		61
Total Labour (h)	8		3
Oct. 15 AM (mm)	73		20
Deep Perc. (mm)	22		4
Total Cost ($/ha)	367		15
Net Returns ($/ha)	-100	(-27.2%)	90

LaW8 TCP 106 ha 50%<III<75% (846437)

	mean		SD
Yield (kg/ha)	3211	(1867)	694
CU (mm)	378		57
WUE (kg/ha/mm)	8.49		
Net Irrigation (mm)	153		49
Total Labour (h)	92		33
Oct. 15 AM (mm)	64		12
Deep Perc. (mm)	14		14
Total Cost ($/ha)	276		24
Net Returns ($/ha)	-27	(-9.8%)	76

Table 4.41 Predicted Irrigated Wheat Results at Lethbridge

LeW1 SCP 25%<I<100% (383838)

	mean		SD
Yield (kg/ha)	2616	(1648)	262
CU (mm)	339		29
WUE (kg/ha/mm)	7.72		
Net Irrigation (mm)	150		45
Total Labour (h)	9		3
Oct. 15 AM (mm)	60		17
Deep Perc. (mm)	2		2
Total Cost ($/ha)	361		18
Net Returns ($/ha)	-182	(-50.4%)	40

LeW2 SCP 50%<I<100% (383838)

	mean		SD
Yield (kg/ha)	3504	(1648)	270
CU (mm)	417		28
WUE (kg/ha/mm)	8.40		
Net Irrigation (mm)	243		47
Total Labour (h)	13		3
Oct. 15 AM (mm)	84		14
Deep Perc. (mm)	8		3
Total Cost ($/ha)	413		22
Net Returns ($/ha)	-70	(-16.9%)	54

Table 4.41 Irrigated Wheat at Lethbridge (continued)

LeW3 SCP 65%<I<85% (275638)

	mean		SD
Yield (kg/ha)	4088	(1697)	197
CU (mm)	461		22
WUE (kg/ha/mm)	8.87		
Net Irrigation (mm)	283		43
Total Labour (h)	20		3
Oct. 15 AM (mm)	72		14
Deep Perc. (mm)	7		6
Total Cost ($/ha)	438		20
Net Returns ($/ha)	4	(0.9%)	50

LeW4 SR1 50.4 ha 50%<I<100%: 3.0,3.0 (383838)

	mean		SD
Yield (kg/ha)	2739	(1648)	309
CU (mm)	348		30
WUE (kg/ha/mm)	7.87		
Net Irrigation (mm)	169		25
Total Labour (h)	104		15
Oct. 15 AM (mm)	67		10
Deep Perc. (mm)	5		3
Total Cost ($/ha)	242		12
Net Returns ($/ha)	-40	(-16.6%)	28

Table 4.41 Irrigated Wheat at Lethbridge (continued)

LeW5 SR2 67.2 ha 50%<I<100%: 3.0,3.0 (383838)

	mean		SD
Yield (kg/ha)	2943	(1648)	254
CU (mm)	367		25
WUE (kg/ha/mm)	8.02		
Net Irrigation (mm)	205		32
Total Labour (h)	172		13
Oct. 15 AM (mm)	80		12
Deep Perc. (mm)	9		4
Total Cost ($/ha)	263		18
Net Returns ($/ha)	-23	(-8.7%)	35

LeW6 SR1 67.2 ha 50%<I<100%: 3.0,3.0 (383838)

	mean		SD
Yield (kg/ha)	2510	(1648)	332
CU (mm)	325		35
WUE (kg/ha/mm)	7.72		
Net Irrigation (mm)	131		15
Total Labour (h)	107		12
Oct. 15 AM (mm)	50		12
Deep Perc. (mm)	3		3
Total Cost ($/ha)	192		8
Net Returns ($/ha)	-33	(-17.2%)	26

Table 4.41 Irrigated Wheat at Lethbridge (continued)

LeW7 SCP 65%<II<100% (365455)

	mean		SD
Yield (kg/ha)	3182	(1416)	226
CU (mm)	370		23
WUE (kg/ha/mm)	8.60		
Net Irrigation (mm)	215		48
Total Labour (h)	16		4
Oct. 15 AM (mm)	50		14
Deep Perc. (mm)	15		3
Total Cost ($/ha)	400		26
Net Returns ($/ha)	-73	(-18.3%)	68

LeW8 SCP 65%<III<100% (365455)

	mean		SD
Yield (kg/ha)	3561	(1452)	197
CU (mm)	407		25
WUE (kg/ha/mm)	8.75		
Net Irrigation (mm)	252		31
Total Labour (h)	18		2
Oct. 15 AM (mm)	52		10
Deep Perc. (mm)	17		16
Total Cost ($/ha)	421		18
Net Returns ($/ha)	-31	(-7.4%)	50

4.5 Concluding Discussion

Irrigation was an effective technique for decreasing the yield variability due to moisture conditions. Generally, the standard deviation of annual irrigated yield was considerably less than that of annual dryland yields. However, the model shows that irrigation does not eliminate variability in yield. Some of the yield variation was predicted to be due to different atmospheric conditions (i.e. PET, sunshine and temperatures) from year to year. In fact, frosts, hail, diseases, and pests are a greater concern with irrigated crop production than with dryland production. Because irrigation increases the operating costs, the returns from irrigated production would be more sensitive to the above losses than the returns from dryland production.

For the side rolls and centre pivot systems, the variable cost of applying one net millimetre of water to the land was about 34% of the value of the increased production of alfalfa which would result from the application of that millimetre of water. In the case of wheat, the equivalent proportion is 29%. For a HHT the proportions are 50% and 41% for alfalfa and wheat, respectively. Since the fixed costs are incurred whether the farmer irrigates or not, the above relationships reveals that, once the irrigation system is purchased, any irrigation during the year will minimize losses.

The considerable variability in annual net returns reveals that in many years the yield improvement from irrigation will be insufficient to cover the costs of irrigation. However, to minimize long-term losses, the farmer must be prepared to irrigate every year. If irrigation is performed only when there is an obvious need, the irrigation system will not pay for itself over its useful lifetime. Essentially all the yield increase due to irrigation is devoted to paying the costs of irrigation. Only the last units of production contribute to profits. The relationship between the variable costs of applying water and the value of the expected increased production emphasizes the importance of irrigating such that crop moisture stress is minimized in all years. Consequently, the irrigator must be a dedicated and hard working individual if irrigation is to be worthwhile.

For the well managed irrigation systems, fixed costs accounted for about 40 to 50% of the total annual irrigation costs. Normally, the annual variable costs of irrigation were paid out of the annual proceeds from irrigation. The challenge for the irrigator is to recoup the fixed costs of the irrigation system.

When a third cut of alfalfa is taken, the profitability of irrigation would be increased substantially. With good management the first two cuts pay for the fixed irrigation costs and variable irrigation costs. Therefore, the third cut only needs to cover the variable irrigation costs incurred in the period following the second cut. In all the situations considered, these variable costs would be less than the value of the third cut yield. Being able to take three alfalfa cuts is most probable in the Dark Brown soil zone because this zone has more degree days than the Black soil zone. With suitable criteria for taking an alfalfa harvest, it would be relatively simple to modify the model so that a third alfalfa cut is taken in favourable years.

The model results highlight the importance of good management on the profitability of irrigation. Irrigation had to be conducted such that the soil was never undesirably depleted of AM from mid June until August. In addition, irrigation was only profitable when soil fertility was well managed and losses due to weeds, pests, and diseases were minimal. As stated previously, increasing the management factor above that assumed would increase annual net returns. Therefore, a farmer who can consistently obtain better yields than those predicted, will also experience greater net returns than estimated.

With good management, irrigation of alfalfa hay could be profitable in the Dark Brown soil zone providing water could be supplied inexpensively to the irrigated land. Considering all factors (especially hail and marketing), irrigation of hard wheat in the Dark Brown soil zone was a marginal investment relative to dryland wheat farming. In the Edmonton area, irrigation of either hard wheat or alfalfa hay was not economically feasible. At Lacombe irrigating alfalfa hay was generally unprofitable. Irrigating hard wheat in the Lacombe area could not be recommended because of unfavourable economics and uncontrollable losses due to hail and frosts.

Hamlin (1983a) studied the economics of supplemental irrigation of hard wheat and alfalfa with a SCP in the portion of Saskatchewan which lies adjacent to east central Alberta. He concluded supplemental irrigation was only economically feasible if all areas of crop production, including irrigation, receive better than average farm management. The model results support his conclusion. Irrigation of alfalfa was profitable with well managed irrigation providing the assumption was made that other factors which affect crop production (especially soil fertility) also received above average farm management. Similarly, supplemental irrigation of hard wheat was only a marginal investment assuming average farm crop management (i.e. M=0.75) even if the irrigation was very well managed. To become a competitive investment, all factors involved in wheat production would have to receive better than average farm management. Supplemental irrigation should be viewed as part of a system of crop production. Only if all aspects of crop production are given careful attention will the maximum increase in net farm income possible with supplemental irrigation be realized.

Any farmer contemplating irrigation should consider the lifestyle changes irrigation demands. The farmer must be prepared to relinquish what would have been spare time with strictly dryland farming and devote that time to irrigating. In this regard, irrigation with a side roll system requires the greatest change in lifestyle while irrigation with a SCP requires the least change.

Of course, irrigating alfalfa is only worthwhile where the alfalfa is needed on the farm where grown or can be sold to an assured market. Probably one of the major limitations to irrigating alfalfa in east central Alberta would be the problem of marketing the irrigated crop every year.

For alfalfa, the irrigation scheduling criteria should be set such that the soil does not become much more than 50% depleted of AM. Because yields and net returns do not decrease substantially until the soil becomes approximately depleted of 65% of the available soil moisture, the above criteria includes a safety factor. If the 50% AM depletion rule is followed then minor interruptions of irrigation due to system breakdowns or other demands on the irrigator's time can be tolerated without irrigation becoming totally uneconomical. The model results indicated there was not a major advantage to irrigating before 50% AM depletion was reached.

Therefore, the model results agree with the often quoted advice that irrigation be started when one-half of the available soil moisture is depleted.

For wheat, the model results suggest that maximum profits are realized if no more than 35% of available soil moisture is depleted. Since yields and net returns do not begin to fall rapidly until 50% or more of the AM is depleted then the 35% AM depletion scheduling criteria includes a safety factor. Minor interruptions of irrigation are possible without making irrigation unprofitable. For hard wheat, the model results differ from the results of irrigation yield trials -- i.e. there is no benefit to irrigating hard wheat before 50% AM depletion is reached. This disagreement may be the result of the model overestimating the effect of moisture stress. The model may place a unrealistic premium on minimizing moisture stress. The component of the wheat yield model which calculates moisture stress could likely benefit from improvements.

The most profitable irrigation systems were the 400 m long centre pivot towed between two positions and a two lateral side roll irrigating 32 ha per lateral. The centre pivot systems demanded considerably less labour than the side rolls or HHT. The HHT and the 220 m long TCP were the least profitable systems -- the former because of its high variable irrigation costs, the latter because of its relatively high fixed costs. Despite its reputation of being overly expensive, the SCP was predicted to be profitable if used to make frequent light irrigations.

The 400 m long TCP could easily be used to irrigate one field of wheat and another of alfalfa. When only alfalfa was irrigated, the pivot was idle during haying. During this time the pivot could be productively used to irrigate the wheat field. Consequently, the yields and returns possible with a TCP would be intermediate between those predicted irrigating only one type of crop with a TCP and those predicted irrigating with a SCP. Irrigating one field of alfalfa and one field of wheat would be clearly desirable from the point of view of diversification. Such an arrangement could ease marketing problems, allow better crop rotations, and spread out the labour needs for harvest. Because the model predicts wheat is more sensitive to moisture stress than alfalfa, the wheat should be irrigated before the alfalfa. This scheme might possibly allow each crop to have near ideal moisture conditions -- less than 35% AM depletion on the wheat land and less than 50% AM depletion on the alfalfa land. Since the 400 m long TCP was among the most profitable systems, irrigating both grain and forage in the same year with the pivot would possibly be the most profitable and desirable irrigation strategy. Relative simple modifications would be required to the model in order to simulate irrigation of several different types of crops with a TCP in the same year.

The major disadvantage of the 400 m long TCP is that it ties up a large portion of the farmer's working capital. Because of the large amount of land irrigated with this system, a large seasonal water supply is necessary to make the system practical. Finally, the system is limited to where the farmer owns two adjacent quarter sections of irrigable land -- neither of which can contain obstructions to the movement of the pivot towers. All these factors clearly limit the number of situations where a 400 m long TCP is suitable.

With the side roll, the yield advantage found when irrigation was begun before 50% AM depletion is probably partly attributable to improved moisture conditions in the last section of the field to be irrigated. That is, if the initial irrigation of the season is started when the soil at the first set reaches 50% AM depletion, the soil at the last set will be undesirably depleted when irrigated. The model indicates the unbalanced moisture condition over the irrigated land area persists to a certain extent over the entire irrigation season. Consequently, the initial irrigation of the season with an intermittent move system should be started before the allowable AM depletion is reached at the first set.

With the TCP, the side roll, and the HHT the amount of land irrigated can be varied without major modifications to the irrigation system. Therefore, an effective way of decreasing the total irrigation costs per hectare is to expand the area irrigated with the above systems. However, as the amount of irrigated land was increased, the timeliness of application was worsened so that irrigated yields decreased and variability in those yields increased. Consequently, there was no advantage in terms of net returns to using an overextended irrigation system over using a system which was sized to approximately meet maximum crop moisture use rates during the year. If reducing yield variability is a major objective of irrigation, the non-overextended irrigation systems are preferable. However, per dollar of annual net returns, the overextended side roll systems required less labour than the adequately sized side roll systems. Therefore, using an overextended side roll may be a satisfactory approach to reducing labour needs for irrigation.

Only a subset of the possible centre pivot, side roll, and HHT irrigation systems were modeled. However, changing the size of the irrigation system primarily changes the irrigation costs. For example, consider a 330 m long SCP. All predicted results except net returns would be the same as for the modeled 400 m long SCP. The economics of irrigating with the 330 m long pivot could be estimated by simply altering the fixed irrigation costs per hectare. Similarly, the principle modification required to examine the economics of irrigating with side rolls with laterals of lengths other than the 400 m considered would be simply inputting the appropriate fixed costs per irrigated hectare.

The model results for the 400 m long SCP, the 400 m long TCP irrigating 106 ha, and the two lateral side roll irrigating 64 ha are summarized for east central Alberta in Table 4.42. These results include the assumption that the additional soil moisture found in the irrigated soils compared with the dryland soils on October 15 is carried forward into the subsequent spring. The quantity of moisture carried forward was adjusted such that the average soil moisture on April 9 would not exceed field capacity. Any moisture which could potentially be carried forward but would raise the available soil moisture above field capacity was, thus, assumed to be lost as deep percolation between October 15 and April 9. This above adjustment was only necessary for wheat stubble soils.

In east central Alberta, the most critical time to irrigate either alfalfa or wheat was from mid June to late July (early June to mid July at Lethbridge). Surprisingly, this period falls during the time of year in which all the locations have the most precipitation. This underlines the fact that crops were predicted to respond to irrigation even if a considerable amount of rain has fallen. Rain was almost never optimal for crop growth in terms of amount or timing. If the irrigator decides to irrigate only when the crop is obviously suffering from

Table 4.42 Summary of Irrigated Results for East Central Alberta (Soil Type I)

System	Yield (kg/ha) mean	Yield (kg/ha) SD	CU (mm) mean	CU (mm) SD	Net Irr. (mm) mean	Net Irr. (mm) SD	Net Ret. ($/ha) mean	Net Ret. ($/ha) SD
Coronation: Alfalfa								
< 50% depl.								
SCP	10007	425	536	27	279	35	4	55
TCP 106 ha	8906	680	491	30	212	29	29	39
SR2 64 ha	9113	612	515	31	242	31	75	42
Coronation: Hard Wheat								
< 35 % depl.								
SCP	3798	142	407	19	209	27	-47	55
TCP 106 ha	3447	168	368	18	160	20	-1	51
SR2 64 ha	3213	209	348	19	180	24	-7	41
Edmonton: Alfalfa								
< 50% depl								
SCP	10712	674	550	30	195	55	-38	70
TCP 106 ha	10008	433	524	35	179	42	-4	43
SR2 64 ha	10104	656	488	34	161	44	5	54
Edmonton: Hard Wheat								
<35% depl.								
SCP	3914	134	418	15	150	49	-106	74
<50% depl.								
TCP 106 ha	3609	207	384	19	100	44	-49	60
SR2 64 ha	3360	720	336	19	99	16	-50	60
Lacombe: Alfalfa								
<50% depl.								
SCP	10913	761	575	33	234	51	7	69
TCP 106 ha	9992	762	543	35	201	39	34	51
SR2 64 ha	9906	499	531	42	200	45	50	46
Lacombe: Hard Wheat								
<35% depl.								
SCP	3706	1129	432	61	163	50	-64	96
<50% depl.								
TCP 106 ha	3464	745	404	61	132	57	-14	72
SR2 64 ha	3095	962	388	67	129	45	-43	50

limited soil moisture, then irrigation will probably decrease farm net income relative to that possible from strictly dryland farming.

Soils with a relatively shallow root zone and a hardpan are the least desirable soils to irrigate. Where a large proportion of the irrigated land area is composed of these soils, irrigation will not likely be profitable.

Irrigation on sandy soils must be managed more carefully than irrigation on soils with a greater AM capacity in the root zone. Sandy soils are best suited to irrigation with a centre pivot. A centre pivot would be best able to maintain a desirably moist root zone.

The model results strongly suggest that the irrigator should concentrate on keeping only the upper one-half to three-quarters of the root zone above the allowable AM depletion. Irrigating the entire root zone to near field capacity is only recommended when leaching is required to maintain a favourable salt balance in the root zone. Otherwise, irrigating until the entire root zone reaches field capacity creates undesirable leaching of plant nutrients below the root zone. In addition, this practice leaves no storage for rains which fall soon after irrigation. Finally, it can delay the movement of the intermittent move irrigation system over the field (because the time spent irrigating each set is increased) which permits undesirable AM depletion in the last part of the field to be irrigated.

In east central Alberta, problems with salinization of the root zone could arise when: i) the soil naturally contains too many salts, ii) the irrigation water contains many dissolved salts, or iii) irrigation raises the local water table so that groundwater brings salts into the root zone. Where leaching is required to remove excess salts or where artificial drainage is needed to remove excess groundwater, the economics of irrigation are less favourable than where leaching or artificial drainage is not necessary. Of course, if the irrigator chooses to let the soil become salinized to increase short-term profits, the land could eventually be rendered almost worthless for either irrigated or dryland agriculture.

Based on the model results, the most desirable technique for reducing irrigation water and labour needs was to cease irrigating just before wheat reaches the soft dough stage and immediately before the alfalfa attains complete ground cover during the second growth. This practice did not decrease net returns significantly in the Black soil zone and only slightly in the Dark Brown soil zone. Shortening the irrigation season forces the crop to use subsurface water stored from earlier rains and/or irrigations.

Several annual crops other than wheat could be irrigated. Two common annual crops grown in east central Alberta are barley and canola. Barley is an attractive crop to irrigate because it uses water more effectively than hard wheat. Consequently, it will respond better to irrigation than hard wheat. However, barley is worth less per tonne than hard wheat. Therefore, economics of irrigating barley in east central Alberta would probably not be much better than for hard wheat. Irrigating canola is appealing because canola is worth more per tonne than hard wheat. In addition, canola is more sensitive to moisture stress than wheat. However, canola does not use water as efficiently as hard wheat so the economics of irrigating canola would probably not be much different than irrigating hard wheat. Soft wheat is a commonly irrigated crop. It shares the same differences with hard wheat as barley -- it characteristically has a greater WUE than hard wheat but has a lower value per tonne. Again, the expected profits irrigating this crop in east central Alberta would not likely be substantially larger than those expected irrigating hard wheat.

Most perennial forages have similar moisture requirements and yield response to water as alfalfa. Therefore, many of the results found for alfalfa could be adapted to other forages. Forage mixtures which do not contain any legumes would require more fertilizer than alfalfa if the forage mixture is to reach its potential yield when moisture is not limiting.

Irrigation is often classed as supplemental if irrigation supplies less than 50% of crop water needs.

Table 4.43 gives the average proportion of crop CU which was derived from irrigation water at all locations on soil type I. These values show that irrigation would be classed as supplemental except for alfalfa at Coronation and Lethbridge. Generally irrigation was not worthwhile unless about 40% or more of crop CU was supplied from irrigation.

Irrigation water was assumed to be applied uniformly across the irrigated land area. The effect of this assumption would not be important where most crop CU is supplied from rain but becomes important when irrigation water constitutes the major source of water for crop growth. In the latter situation, any part of the field which receives less irrigation than assumed would not likely have yields as large as predicted. The problem of assuming uniform application would be aggravated when one portion of the field consistently receives less irrigation water than assumed by the irrigator. Such a situation is common when one part of the irrigated land area is higher in elevation than the remainder of the irrigated area -- especially if the elevated portion is also farther from the pump than the rest of the irrigated land. In the latter area sprinkler pressures would be less than other areas and so the application rate would be less than assumed. The model could be modified to account for the effect of uneven application of irrigation water. Each irrigated position could be subdivided into a number of

Table 4.43 Fraction of Crop CU Supplied by Irrigation

	SCP < 35% AM depl.		SR2 64 ha < 50% AM depl.	
Location	Alfalfa	Wheat	Alfalfa	Wheat
Coronation	0.52	0.41	0.47	0.31
Edmonton	0.37	0.27	0.27	0.17
Lacombe	0.44	0.33	0.36	0.26
Lethbridge	0.59	0.48	0.52	0.34

individual soil-crop areas. Each of these smaller areas would need to be modeled independently. A function could be chosen which predicts the probability of receiving a specific amount of irrigation water given the planned irrigation application. The amount of irrigation each area receives could then be randomly selected within the specific probabilities. The above change would increase the running cost of the model. For example, if each irrigated position was subdivided into three smaller areas, the running costs would be approximately tripled.

One additional way which the simulation could be improved is to include the effect of hail damage. For insurance purposes, the approximate probability of hail occurring at any specific location along with the probability of expected crop damage have been determined.

Using these probabilities, it would be comparatively simple to generate hail damage on a random basis.

The model uses fairly detailed daily weather data. Therefore, it should be possible to estimate the effect weather would have on the harvest processes and the effect of weather during harvesting on the quantity and quality of the harvested crop.

Including the effect of harvest weather and hail on crop yield and value would increase the ability of the model to estimate the impact irrigation could have on decreasing the variability of gross farm returns. This would improve the utility of the model as a aid to analyze the feasibility of irrigation in any one particular area.

Comparing the model results for the two locations in the Dark Brown soil zone reveals that irrigation was predicted to be more beneficial in southern Alberta than in east central Alberta. In addition, comparing weather at Coronation with weather at Lethbridge reveals that droughts are worse at Lethbridge. Furthermore, the consequences of droughts are greater at Lethbridge because PET is greater there. Therefore, expansion of irrigated land area in southern Alberta should have priority over developing irrigated land area in east central Alberta.

To a large extent the study was heuristic in that the availability of a supply of irrigation water was essentially ignored. However, two important conclusions regarding the the irrigation water supply can be drawn from the model results:

i) no investment in irrigation should be made unless there is sufficient water for full irrigation throughout the summer, and

ii) irrigation will probably not be profitable if large fixed and/or variable costs must be incurred to bring water to the irrigated land.

Unfortunately, suitable water sources are scarcer in the drier southeastern corner of Alberta where irrigation is most beneficial than in the wetter remainder of the province. Presently, expensive and complex water distribution systems are required in southern Alberta to supply irrigating farmers with water throughout the growing season. The model results indicate that if the entire costs of the water distribution system were borne by the irrigating farmers alone, irrigated agriculture in southern Alberta would become less attractive than dryland agriculture. Therefore the model results concur with the conclusion of the Environmental Council of Alberta (1982) that irrigated agriculture must be subsidized by the rest of society if it is to be economically viable in the long term.

The question of government subsidies for farmers who use irrigation is entirely political. However, presently the provincial government justifies subsidies to farmers who form an irrigation district by claiming that most benefits from irrigation are reaped by society at large.

The fundamental principle of promoting equity among all citizens is firmly entrenched in the Canadian political system. Hence, insofar as farmers belonging to an irrigation district receive government subsidies, equivalent subsidies should be made available to private irrigators throughout Alberta who do not belong to an irrigation district.

Similar subsidies as those presently provided by the Saskatchewan government (Saskatchewan Agriculture 1984) to beginning irrigators would substantially improve the feasibility of supplemental irrigation in east central Alberta. Since the subsidies are made available during the first three years the farmer irrigates, the net effect of subsidies is to reduce the capital cost of the irrigation system to the farmer. The subsidies could decrease the annual fixed costs of irrigation by 15 to 25% which, in turn, could reduce average total annual irrigation costs by 5 to 15%. This would significantly increase the profitability of irrigation and make irrigation of alfalfa at Edmonton and Lacombe and irrigation of wheat at Coronation economically justifiable. Giving the subsidies during the first few years of irrigation is particularly beneficial for the farmers. During this period yields with irrigation may not be as large as otherwise expected and yet the need for cash inflows may be at a maximum.

Irrigated agriculture forms a fairly complex system when the effect of management of the irrigation system is included. Thus, the approach of evaluating the feasibility of the supplemental irrigation by using a computer simulation model was appropriate. However, it is essential that one realizes that a computer simulation is a supplement to and not a replacement for actual experimentation.

One of the major advantages of a computer simulation model is that the researcher is forced to quantify all assumptions so that they can be implemented within a computer program. Thus, other researchers can relatively easily build onto the work that has already been accomplished.

To assess the feasibility of irrigating one parcel of land requires an integrated evaluation of land, weather, crops, water supply, and the abilities and attitudes of the farm manager. Futhermore, a specific evaluation must consider tax effects for the farming operation and the financial objectives of the owner of the farm. A computer model of the sort used in this study can be a valuable aid in the assessment of feasibility of irrigation. Specific irrigation costs, expected crop prices, soil moisture properties, weather, and expected management practices can be inputted into the model. The model can then estimate crop yields and net returns.

As implemented, the model used for this study would not appear to be an appropriate tool for helping an irrigator make real time irrigation scheduling decisions. Presently, the model results must be analyzed in a statistical context and do not produce a clear yes-no decision of whether to irrigate a given field this day or wait for several days.

The model is suited for use as an aid in selecting an irrigation system for a specific area. The model can be used to test a variety of irrigation systems at one location. The performance of each system with regard to predicted yields, water requirements, labour needs, capital requirements, and annual economic returns can be examined. With the helpful interpretation by a knowledgeable technician, such information would be invaluable for a farmer contemplating investing in supplemental irrigation. The model results would also demonstrate the importance of management on the success or failure of the irrigation project.

Overall, the results produced by the model were not unexpected. They conformed with anticipated results. Interestingly, the results sometimes supported conventional farm practice rather than the views of irrigation professionals who work in the public service. For instance, the results confirmed the value of the practice of using a centre pivot to wet only the upper portion of the root zone as a technique for minimizing labour needs while still producing satisfactory yields and returns.

Although the model contains numerable simplifications and inaccuracies, it produced serviceable estimates of yields and CU under a broad variation of growing season moisture conditions. The yield modeling component was the weakest part of the entire simulation model. The yield estimation model developed for the model was certainly far from ideal. However, its relative simplicity coupled with its ability to provide acceptable estimates of yields under a wide variety of moisture conditions indicates the yield model is superior to most yield models found in the literature.

The study has shown that supplemental sprinkler irrigation in east central Alberta has limited economic feasibility. Irrigation was found to be profitable only for perennial forages in the Dark Brown soil zone of east central Alberta. Furthermore, irrigation was only a worthwhile investment where irrigable land and a good water source were already contiguous. Irrigation had to be started whenever the soil became undesireably depleted of available soil moisture -- 50% AM depletion for alfalfa and 35% AM depletion for wheat. If all the conditions were met then supplemental sprinkler irrigation could be a viable alternative to buying additional farmland and/or an effective strategy for improving annual net farm income.

5.0 Conclusions

1) Evaluating the feasibility of supplemental irrigation for an individual farm should involve specific study of the: i) irrigability of the land, ii) available water supply, iii) availability of labour, iv) exact variable and fixed irrigation costs associated with the irrigation systems under consideration, v) abilities and attitudes of the farm operator, vi) objectives of the farm operator, vii) tax and financial considerations, and viii) marketing of the irrigated production.

2) A computer simulation model was a valuable and relatively inexpensive technique for producing estimates of the profitability of supplemental irrigation and of the effects of changing irrigation practices.

3) Irrigation was not feasible unless there was sufficient water, labour, and dedication to maintain the soil continually moist throughout the irrigation season. Maximum profits were possible when depletion of available soil moisture in the root zone did not exceed 50% for alfalfa and 35% for hard wheat. Irrigation was only profitable where irrigation water could be supplied at minimal cost. The major limitation to the

development of supplemental irrigation was the cost and availability of irrigation water.

4) With good management, irrigation of alfalfa in the Dark Brown soil zone (Coronation and Lethbridge) was profitable. Irrigated alfalfa yields were more than double dryland yields in the Dark Brown soil zone. In the Black soil zone (Edmonton and Lacombe) irrigated alfalfa yields were approximately double dryland alfalfa yields. However, irrigating alfalfa at Edmonton was not economically feasible and was a marginal investment at Lacombe.

5) In the Black soil zone (Edmonton and Lacombe) irrigated wheat yields were only approximately 50% more than dryland yields. Consequently, irrigating hard wheat at Edmonton or Lacombe was not as financially renumerative as dryland wheat production. In the Dark Brown soil zone (Coronation and Lethbridge), with good management, supplemental irrigation could almost double dryland yields. However, at Coronation and Lethbridge, irrigation of hard wheat was marginally profitable.

6) Of the irrigation systems considered, the most profitable was a 400 m long centre pivot towed between two positions and a side roll with two 400 m long laterals irrigating an entire quarter section. Where

conditions are suitable for a 400 m long towable centre pivot, the best practice would probably be to irrigate one field of grain and one field of perennial forage. The hard hose reel traveler and the 220 m long towable centre pivot were the least profitable irrigation systems. A 400 m long stationary centre pivot could be economical if it was used to make frequent, relatively light applications. There was no clear advantage to using an overextended side roll irrigation system over a side roll which was adequate to meet maximum seasonal crop water use rates.

7) Maintaining the upper one-half to two-thirds of the root zone less than 50% depleted of plant available moisture was a successful practice for using irrigation water and labour most efficiently. Irrigating the entire root zone to field capacity was disadvantageous because it increased irrigation costs without increasing yields. There was little reduction in yields or net returns when irrigation of wheat was stopped when the soft dough stage was reached. Similarly, there was little loss in yields and net returns when irrigation of alfalfa was ceased after full ground cover was attained during the second growth. When the seasonal water supply was moderately restricted, it was better to limit the irrigations at the end of the irrigation season than to allow greater

than desired depletion of available moisture at the beginning of the irrigation season. Both hard wheat and alfalfa were most responsive to irrigation from mid-June to early August in east central Alberta and from early June to late July in southern Alberta.

8) Crops grown on soils with a hardpan which restricts both rooting depth and moisture penetration were the least responsive to irrigation. Irrigating coarse textured soils was only profitable when it was managed very carefully so as to ensure the root zone did not become undesirably depleted of available moisture.

9) The economics of supplemental irrigation in east central Alberta were such that any government subsidies to support irrigation could make sprinkler irrigation an attractive investment. Because southern Alberta has larger expected moisture deficits, supplemental irrigation in southern Alberta was more beneficial than in east central Alberta.

6.0 Recommendations for Future Work

1) An assessment of the quantity and quality of water supplies available for supplemental irrigation is needed in east central Alberta. Because of the predicted economics, the assessment should concentrate on the Dark Brown soil zone within east central Alberta. In addition, the assessment should also inventory the amount and quality of irrigable land near the most suitable water sources for irrigation.

2) All components of the computer simulation model require further verification. Irrigation field trials are necessary in east central Alberta to test the validity of the model. Throughout Alberta, research is needed to determine the optimal irrigation practices for a stationary centre pivot.

3) A number of potential improvements to the computer simulation model have already been discussed. These are outlined below:

   i) change the weather model so that it better takes into account trends of above or below normal potential evapotranspiration.

ii) model soil moisture for the entire year.

iii) alter the alfalfa development model so that the start of spring growth is delayed and the number of degree days to reach the cutting stage is reduced.

iv) The criteria for taking the second alfalfa harvest should be changed to consider date, cumulative yield, and amount of plant available soil moisture when the alfalfa is ready to cut.

v) permit taking of a third alfalfa cut when conditions are favourable.

vi) include the effects of hail on yield and the effects of weather during crop harvesting on quantity and quality of crop yield.

vii) alter the wheat yield model so that yield reduction due to moisture stress is reduced in the Dark Brown soil zone.

viii) permit greater extraction of available moisture from the lower portion of soils which have a relatively small capacity for available moisture in the root zone.

ix) adjust late season root extraction (i.e. k) coefficients to better model evapotranspiration after the second cut of alfalfa and after the wheat has been harvested.

x) modify the model so that more than one type of crop can be irrigated with a towable centre pivot irrigation system.

xi) include the effect of uneven application of irrigation

8.0 References

Alberta Agriculture, 1981a, Management of Solonetzic Soils, Agdex 516-8, Alberta Agriculture, Edmonton, 2pp.

Alberta Agriculture, 1981b, Fall Irrigation, Agdex 563-2, Alberta Agriculture, Edmonton, 2 pp.

Alberta Agriculture, 1981c, Irrigating Forage Crops in the Peace River Country, Agdex 120/561-1, Alberta Agriculture, Edmonton, 2 pp.

Alberta Agriculture, 1982, Irrigation in Alberta, Agdex 560-1, Alberta Agriculture, Edmonton, 11 pp.

Allen, L.C. and K. Elgaard, 1963, Irrigation Lands Crop Production Study, All Irrigation Districts, Alberta, 1963, Economics Branch, Canada Department of Agriculture, 45 pp.

Apland, J., B.A. McCarl and W.L. Miller, 1980, Risk and the Demand for Supplemental Irrigation: A Case Study in the Corn Belt, Amer. J. of Agr. Econ. 62:142-145.

Atmospheric Environment Service, Monthly Record of Meteorological Observations in Western Canada, Environment Canada, Toronto, various volumes.

Army, T.J., J.J. Bond and C.E. Van Doren, 1959, Precipitation-Yield Relationships in Dryland Wheat Production on Medium to Fine Textured Soils of the Southern High Plains, Agron. J. 51:721-724.

Ayers, H.D., 1965, Water Deficit and Irrigation Needs in Ontario, Can. Agr. Eng. 7:37-39.

Baier, W., 1971, Evaluation of Latent Evaporation Estimates and Their Conversion to Potential Evaporation, Can. J. Pl. Sci. 51:255-266.

Baier, W., 1973, Crop-Weather Analysis Model: Review and Model Development, J. Applied Met. 12:937-946.

Baier, W., J.A. Dyer and W.R. Sharp, 1979, The Versatile Soil Moisture Budget, Tech. Bull. 87, Agrometeorology Section, Land Resource Research Institute, Research Branch, Agriculture Canada, Ottawa, 52 pp.

Baier, W. and G.W. Robertson, 1965, Estimation of Latent Evaporation from Simple Weather Observations, Can. J. Pl. Sci. 45:276-284.

Baier, W. and G.W. Robertson, 1966, A New Versatile Soil Moisture Budget, Can. J. Pl. Sci. 46:299-315.

Baier, W. and G.W. Robertson, 1967a, Estimating Yield Components of Wheat from Calculated Soil Moisture, Can. J. Pl. Sci. 47:617-630.

Baier, W. and G.W. Robertson, 1967b, Estimating Supplemental Irrigation Water Requirements from Climatological Data, Can. Agr. Eng. 9:46-50.

Baier, W. and G.W. Robertson, 1968, The Performance of Soil Moisture Estimates as Compared with Direct Use of Climatological Data for Estimating Crop Yields, Agr. Met. 5:17-31.

Baier, W. and G.W. Robertson, 1970, Climatic Estimates of Average and Probable Irrigation Requirements and of Seasonal Drainage in Canada, J. of Hydrology, 10:20-37.

Baier, W. and D.A. Russelo, 1968, A Computer Program for Estimating Risk of Irrigation Requirements from Climatological Data, Tech. Bull. 59, Agrometeorology Section, Plant Research Institute, Research Branch, Agriculture Canada, Ottawa, 31 pp.

Barteski, L., 1983, Drainage of Irrigated Soil, Publ. 83.11, Saskatchewan Agriculture, Regina, 14 pp.

Bauder, J.W., A. Bauer, J.M. Ramirez and D.K. Cassel, 1978, Alfalfa Water Use on Dryland and Irrigated Sandy Loam, Agron. J. 70:95-99.

Bauer, A., 1971, Effect of Water Supply and Seasonal Distribution on Spring Wheat Yields, Bull. 490, Agr. Exp. Stat., North Dakota State Univ., 22 pp.

Bauer, A., R.A. Young and J.L. Olson, 1965, Effects of Moisture and Fertilizer on Yield of Spring Wheat and Barley, Agron. J. 57:354-356.

Bezeau, L.M. and L. G. Sonmor, 1964, The Influence of Levels of Irrigation on the Nutritive Value of Alfalfa, Can. J. Pl. Sci. 44:505-508.

Bras, R.L. and J.R. Cordova, 1981, Intraseasonal Water Allocation in Deficit Irrigation, Water Resour. Res. 17:866-874.

Brocke, L.K., 1977, Soil Capability for Agriculture in Alberta, Alberta Environment, Edmonton, 24 pp.

Burman, R.D., P.R. Nixon, J.L. Wright and W.O. Pruitt, 1980, Water Requirements, in: M.E. Jensen, ed., Design and Operation of Farm Irrigation Systems, ASAE, St. Joseph, MI, pp. 189-232.

Burt, O.R. and M.S. Stauber, 1971, Economic Analysis of Irrigation in a Subhumid Climate, Amer. J. Agr. Econ. 53:33-46.

Canada Soil Survey Committee, 1978, The Canadian System of Soil Classification, Publ. 1946, Agriculture Canada, Ottawa, 164 pp.

Cairns, R.R. and W.E. Bowser, 1977, Solonetzic Soils and Their Management, Publ. 1371, Agriculture Canada, Ottawa, 36 pp.

Daigger, L.A., L.S. Axthelm and C.L. Ashburn, 1970, Consumptive Use of Water by Alfalfa in Western Nebraska, Agron. J. 63:507-508.

Davies, F.D. 1971, Evapotranspiration/Evaporation Ratios for Northern Alberta, Water Resources Division, Alberta Department of Agriculture, Edmonton, 30 pp.

de Jong, E. and D.R. Cameron, 1980, Efficiency of Water Use by Agriculture for Dryland Crop Production, Proceedings of Prairie Production Symposium, Canadian Wheat Board, Saskatoon, October 1980, various pagination.

de Jong, R. and C.F. Shaykewich, 1981, A Soil Water Budget Model with a Nearly Impermeable Layer, Can. J. Soil Sci. 61:361-371.

de Jong, R., 1981, Soil Water Models: A Review, Research Branch, Agriculture Canada, Ottawa, 39 pp.

Doorenbos, J. and A.H. Kassam, 1979, Yield Response to Water, FAO Irrigation and Drainage Paper 33, FAO, Rome, 193 pp.

Doorenbos, J. and W. Pruitt, 1977, Guidelines for Predicting Crop Water Requirements, FAO Irrigation and Drainage Paper 24, FAO, Rome, 144 pp.

Dudley, N.J., D.T. Howell and W.F. Musgrave, 1971, Optimal Intraseasonal Irrigation Water Allocation, Water Resour. Res. 7:770-778.

Dyer, J.A., W. Baier, H.N. Hayhoe and G. Fisher, 1978, Spring Field Workday Probabilities for Selected Sites Across Canada, Tech. Bull. 86, Agrometeorology Section, Land Resource Research Institute, Research Branch, Agriculture Canada, Ottawa, various pagination.

Dylla, A.S., H. Shull and D.R. Timmons, 1980, Computer Simulation of Sprinkler Irrigation Practices for Minnesota, Trans. ASAE 23:1419-1423.

Eagleman, J.R., 1971, An Experimentally Derived Model for Actual Evapotranspiration, Agr. Met. 8:385-394.

Ehlig, C.F., and R.D. LeMert, 1976, Water Use and Productivity of Wheat Under Five Irrigation Treatments, Soil Sci. of Amer. J. 40:750-755.

English, M.J., 1981, The Uncertainity of Crop Models in Irrigation Optimization, Trans. ASAE 24:917-928.

Environment Council of Alberta, 1978, Management of Groundwater Resources in Alberta, Environment Council of Alberta, Edmonton, 45 pp.

Environment Council of Alberta, 1982, Irrigation Agriculture in Alberta, Publ. ECA 81-17/IB8, Environment Council of Alberta, Edmonton, 74 pp.

Farm Business Management Branch, 1981, Farm Management Data Manual, Alberta Agriculture, Edmonton, various pagination.

Farm Business Management Branch, 1983, Farm Machinery Costs as a Guide to Custom Rates, Agdex 825-4, Alberta Agriculture, Edmonton, 17 pp.

Farm Business Management Branch, 1984, Custom Rates: Annual Survey Summary 1983, Agdex 825-9, Alberta Agriculture, Edmonton, 23 pp.

Feddes, R.A., P.J. Kowalik, and H. Zaradny, 1978, Simulating Field Water Use and Crop Yield, John Wiley and Sons, N.Y., 188 pp.

Feyerherm, A.M. and L.D. Bark, 1967, Goodness of Fit of a Markov Chain Model for Sequences of Wet and Dry Days, J. Applied Met. 6:770-773.

Flinn, J.C. and W.F. Musgrave, 1967, Development and Analysis of Input-Output Relations for Irrigation Water, Austral. J. of Agr. Econ. 11:1-19.

Gardner, E.J., L.D. Schall and C.W. Haley, 1981, Introduction to Financial Management, McGraw Hill-Ryerson Ltd., Toronto, 817 pp.

Gavande, S.A. and S.A. Taylor, 1967, Influence of Soil Water Potential and Atmospheric Evaporative Demand on Transpiration and the Energy Status of Water in Plants, Agron. J. 59:4-7.

Gray, D.M., J.M. Murray and W. Nicholaichuk, 1966, Frequency of Occurrence of Evapotranspiration Extremes as Applied to the Design of Irrigation Systems, Can. Agr. Eng. 8:12-14, 39.

Gray, D.M., R.J. Granger and G.E. Dyck, 1983, Overwinter Soil Moisture Changes, ASAE paper 83-2513, 20 pp.

Guide to Farm Practice in Saskatchewan, 1981, Division of Extension and Community Relations, University of Saskatchewan, Saskatoon, 216 pp.

Hall, W.A and W.S. Butcher, 1968, Optimal Timing of Irrigation, J. Irr. and Drain. Div. ASCE, 94:257-267.

Hamlin, T.W., 1983a, Can Irrigated Hard Wheat Pay in '83?, Publ. 83.02, Saskatchewan Agriculture, Regina, 9 pp.

Hamlin, T.W., 1983b, Irrigated Land Assessment, Publ. 81.07, Saskatchewan Agriculture, Regina, 6 pp.

Hamlin, T.W., 1983c, Irrigation and Population, Publ. 83.40, Saskatchewan Agriculture, Regina, 4 pp.

Hamlin, T.W., 1983d, Transition to Irrigation, Publ. 83.17, Saskatchewan Agriculture, Regina, 2 pp.

Hamlin, T.W., 1983e, Why Irrigate?, Publ. 83.18, Saskatchewan Agriculture, Regina, 4 pp.

Hart, W.E., D.I. Norum and G. Peri, 1980, Optimal Seasonal Irrigation Application Analysis, J. Irr. and Drain. Div. ASCE 104:221-235.

Haun, R.W., 1974, Prediction of Spring Wheat Yields from Temperature and Precipitation Data, Agron. J. 66:405-409.

Hausenbuiller, R.L., 1978, Soil Science: Principles and Practices, Wm C. Brown Company Publisher, Dubuque, Iowa, 611 pp.

Heermann, D.F., H.H. Shull and R.H. Mickelson, 1974, Centre Pivot Design Capacities in Eastern Colorado, J. Irr. and Drain. Div. ASCE, 100:127-141.

Heywood, R.T., R.D. Neilson and D. Eriksen, 1972, Irrigation Studies 1971: Annual Report, Land Development Branch, Water Resources Division, Alberta Environment, Edmonton, 56 pp.

Hill, R.W. and J. Keller, 1980, Irrigation System Selection for Maximum Crop Profit, Trans. ASAE 23:366-372.

Hinman, W.C., 1974, Effects of Fertilizer and Available Moisture on Yield and Nitrogen and Phosphorus Content of Wheat and on Soil Nutrients, Can. J. Soil Sci. 54:187-193.

Hobbs, E.H. and K.K. Krogman, 1966, A Comparison of Measured and Calculated Evapotranspiration for Alfalfa in Southern Alberta, Can. Agr. Eng. 8:9-11.

Hobbs, E.H. and K.K. Krogman, 1968, Observed and Estimated Evapotranspiration in Southern Alberta, Trans. ASAE 11:502-503, 507.

Hobbs, E.H. and K.K. Krogman, 1970, Evaluation of a Method of Irrigation Scheduling, Can. Agr. Eng. 12:25-27.

Hobbs, E.H. and K.K. Krogman, 1978, Frequent Light Irrigation Scheduling to Improve Efficiency of Water Use, Can. Agr. Eng. 20:109-112.

Hobbs, E.H., K.K. Krogman and L.G. Sonmor, 1963, Effects of Levels of Minimum Available Soil Moisture on Crop Yields, Can. J. Pl. Sci., 43:441-446.

Holmes, R.M. and G.W. Robertson, 1963, Application of the Relationship Between Actual and Potential Evapotranspiration in Dry Land Agriculture, Trans. ASAE 6:65-67.

Holt, D.A., C.T. Dougherty, G.E. Miles, R.J. Bula, M.M. Schreiber and R.M. Peart, 1978, SIMED, A Computerized Simulation Model of Alfalfa, ASAE paper 78-4034, 15 pp.

Hopkins, J.W. and P. Robillard, 1964, Some Statistics of Daily Rainfall Occurrence for the Canadian Prairie Provinces, J. Applied Met. 3:600-602.

Howell, T.A., Hiler, E.A. and D.L. Reddell, 1975, Optimization of Water Use Efficiency under High Frequency: II System Simulation and Dynamic Programming, Trans. ASAE 18:879-887.

Jensen, M.E. 1968, Water Consumption by Agricultural Plants, in: Kozlowski, T.T., ed., Water Deficits and Plant Growth, Vol. 2, Academic Press, N.Y., pp. 1-22.

Jensen, M.E., J.L. Wright and B.J. Pratt, 1971, Estimating Soil Moisture Depletion from Climate, Crops and Soil Data, Trans. ASAE 14:954-957.

Johnston, K.E. and J. Hendricks, 1974, Precipitation Probabilities at Regina, Tech. Memoranda 809, Atmospheric Environment Service, Environment Canada, Downsview, ON, 5 pp.

Jones, J.W., R.F. Colwick and E.D. Threadgill, 1972, A Simulated Model of Temperature, Evaporation, Rainfall, and Soil Moisture, Trans. ASAE 15:366-372.

Karkanis, P.G., 1982, Land Irrigability Classification in Alberta, Proceedings of the 19th Annual Alberta Soil Science Workshop, Alberta Agriculture, Edmonton, pp. 25-48.

Kendall, G.R., 1966, Probability Distribution of a Single Variable, in Statistical Methods in Hydrology, Proceedings of Hydrology Symposium No. 5, February 1966, Canada Department of Energy Mines and Resources, Ottawa, pp. 41-51.

Kirkam, M.B. and E.T. Kanemasu, 1983, Wheat, in: I.D. Teare and M.M. Peet, eds., Crop-Water Relations, John Wiley and Sons, N. Y., pp. 481-520.

Korven, H.C. and M.R. Kilcher, 1979, Length of Irrigation Season and Various Start-Stop Times and Their Effect on Alfalfa Production and Persistence, ASAE paper 79-2096, 14 pp.

Korven, H.C. and W.L. Pelton, 1967, Advection in Southwest Saskatchewan, Can. Agr. Eng. 9:88-90, 124.

Korven, H.C. and W.E. Randall, 1975, Irrigation on the Prairies, Publ. 1488, Agriculture Canada, Ottawa, 26 pp.

Korven, H.C. and J.K. Wiens, 1974, Evaluation of an Over-Extended Irrigation System, Can. Agr. Eng. 16:51-56.

Kreith, F. and W. Black, 1980, Basic Heat Transfer, Harper and Row, N.Y. 556 pp.

Krogman, K.K. and E.H. Hobbs, 1965, Evapotranspiration by Irrigated Alfalfa as Related to Season and Growth Stage, Can. J. Pl. Sci. 45:309-313.

Krogman, K.K. and E.H. Hobbs, 1976, Scheduling Irrigation to Meet Crop Demands, Publ. 1590, Agriculture Canada, Ottawa, 18 pp.

Lake, E.B. and R.S. Broughton, 1969, Irrigation Requirements in South Western Quebec, Can. Agr. Eng. 11:28.31, 38.

Larson, R.E. and J.L. Casti, 1978, Principles of Dynamic Programming, Marcel Dekker, N.Y., Part I, 330 pp., and Part II, 497 pp.

Lehane, J.J. and W.J. Staple, 1965, Influence of Soil Moisture Storage and Rainfall Distribution on Wheat Yield in Southwestern Saskatchewan, Can. J. Soil Sci. 45:207-219.

Lembke, W.D. and B.A. Jones, 1972, Selecting a Method for Scheduling Irrigation Using A Simulation Model, Trans. ASAE 15:284-286.

Linsley, J., 1983, Irrigation Cash Flow, Publ. 83.15, Saskatchewan Agriculture, Regina, 4 pp.

Linsley, J. and T.W. Hamlin, 1984, Projected Costs and Yields: Irrigated Crops: Outlook Area 1984, Saskatchewan Agriculture, Regina, 13 pp.

Longley, R.W., 1972, The Climate of the Prairie Provinces, Climatological Studies No. 13, Atmospheric Environment Service, Environment Canada, Toronto, 79 pp.

Loucks, D.P., J.R. Stedinger and D.A. Haith, 1981, Water Resource Systems Analysis, Prentice Hall Inc., Englewood Cliffs, N.J., 559 pp.

Lyster, B., 1984, Irrigating on the Move, Country Guide, 103(4):20-21.

Mapp, H.P., V.R. Eidman, J.F. Stone and J.M. Davidson, 1975, Simulating Soil Water and Atmospheric Stress-Crop Yield Relationships for Economic Analysis, Tech. Bull. T-140, Agr. Exp. Stat., Oklahoma State Univ., 63 pp.

Martin, D., D.F. Heermann, J.R. Gilley and J.W. Labadie, 1983, Optimal Seasonal Centre Pivot Management, ASAE paper 83-2004, 30 pp.

Merva, G.E., 1975, Physioengineering Principles, The AVI Publishing Co. Inc., N.Y., 353 pp.

Minhas, B.S., K.S. Parikh and T.N. Srinivasan, 1974, Toward the Structure of a Production Function for Wheat Yields with Dated Inputs of Irrigation Water, Water Resour. Res. 10:983-393.

Morin, T.L., 1973, Pathology of a Dynamic Programming Sequencing Algorithm, Water Resour. Res. 9:1178-1185.

Muir, W.E., 1979, Basic Thermal Processes in Agriculture, University of Manitoba, Winnipeg, various pagination.

Neghassi, H.M., D.F. Heermann and D.E. Smith, 1975, Wheat Yield Models with Limited Soil Water, Trans. ASAE 18:549-557.

Nelson, C.J. and D. Smith, 1964, Growth of Birdsfoot Trefoil and Alfalfa, III Changes in Growth Analysis Under Field Conditions, Crop Sci. 8:25-28.

Otterby, M.A. and D.W. DeBoer, 1977, Economic Analysis of Multiple Pivot Irrigation on a Droughty Soil, ASAE paper 77-2006.

Palmer, J.C., 1982, Changes in Chemical Properties of Solonetzic Soils under Irrigation, in: Proceedings of the 19th Annual Alberta Soil Science Workshop, Alberta Agriculture, Edmonton, pp. 49-59.

Pearson, C.J. and L.A. Hunt, 1972, Effects of Temperature on Primary Growth of Alfalfa, Can. J. Pl. Sci. 52:1007-1015.

Pelton, W.L., 1964, Evaporation from Atmometers and Pans, Can. J. Pl. Sci. 44:397-404.

Pelton, W.L. and H.C. Korven, 1969, Evapotranspiration Estimates in a Semiarid Climate, Can. Agr. Eng. 11:50-53, 61.

Penman, H.L., 1948, Natural Evaporation from Open Water, Bare Soil, and Grass, Proc. Roy. Soc., 193:120-145.

Penman, H.L., 1956, Evaporation: An Introductory Survey, Neth. J. Agr. Sci. 4:9-29.

Peters, T.W., 1977, Relationships of Yield Data to Agroclimatic Soil Capability Classification and Soils of Alberta, Can. J. Soil Sci. 57:341-347.

Peters, T.W. and W.W. Pettapiece, 1981, Crop Yields in Alberta: Preliminary Relationships to Soil Capability for Agriculture and Soil Type, Alberta Institute of Pedology, University of Alberta, Edmonton.

Peters, T.W., J.A. Shields and J.G. Ellis, 1978, Guidebook for a Tour to Observe Soil Landscapes and Cropping Systems in Central and Southern Alberta and South-Western Saskatchewan, Soil Research Institute Contribution No. 652, Agriculture Canada, Ottawa, 171 pp.

Pittman, U.J., 1973, Crop Production Potentials in the Brown, Dark Brown and Thin Black Soil Zones, in: Crop Production Potential in Alberta: Proceedings of the Alberta Soil Science Workshop, December, 1973, Alberta Agriculture, Edmonton, pp. 9-24.

Pohjakas, K., D.W.L. Read and H.C. Korven, 1967, Consumptive Use of Water by Crops at Swift Current, Saskatchewan, Can. J. Soil Sci. 47:138-138.

Pohjakas, K., 1981, Evaluation of Centre Pivot Irrigation Practices in Alberta, ASAE PNW paper 81-204, 14 pp.

Purnell, J.C., 1982, Irrigation Development in Canada: 1982, in: Annual Technical Conference Proceedings, Irrigation Association, pp. 309-321.

Rapp, E., L.P. Apedaile and R. Desjardins, 1983, Slough and Wet Land Problems in East Central Alberta, Can. Agr. Eng. 25:11-18.

Rasmussen, V.P. and R.J. Hanks, 1978, Spring Wheat Yield Model for Limited Moisture Conditions, Agron. J. 70:940-944.

Rhenals, A.E. and R.L. Bras, 1981, The Irrigation Scheduling Problem and Evapotranspiration Uncertainty, Water Resour. Res. 17:1328-1338.

Richardson, C.W., 1979, Simulation of Daily Weather Variables, ASAE paper 79-2021, 11 pp.

Ring. L. 1984, Cost Comparisons of Irrigation Systems, Alberta Agriculture, Lethbridge, 1 p.

Robertson, G.W., 1968, A Biometeorological Time Scale for a Cereal Crop Involving Day and Night Temperatures and Photoperiod, Int. J. Biomet. 12:191-223.

Robertson, G.W., 1974, Wheat Yields for 50 Years at Swift Current, Saskatchewan in Relation to Weather, Can. J. Pl. Sci. 54:625-650.

Sammis, T.W., A.S. Abdul-Jabber and D.G. Lugy, 1983, Influence of Available Soil Water on Modeling Crop Growth, ASAE paper 83-2125.

Saskatchewan Agriculture, 1984, Individual Irrigation Development Policy, Saskatchewan Agriculture, Regina, 2 pp.

Saxton, K.E., H.P. Johnston and R.H. Shaw, 1974, Modeling Evapotranspiration and Soil Moisture, Trans. ASAE 17:673-677.

Scott, D.W., 1975, Irrigation and Drainage as Influenced by Weather: A Simulated Model, unpublished M.Sc. thesis, Department of Agricultural Engineering, University of Alberta, Edmonton, 144 pp.

Selerio, I.S., D.M. Brown and K.M. King, 1971, Estimation of Net and Solar Radiation, Can. J. Pl. Sci. 51:35-39.

Selirio, I.S. and D.M. Brown, 1979, Soil Moisture-Based Simulation of Forage Yield, Agr. Met. 20:99-114.

Simpson, W. and C.D. Henry, 1966, Dry and Wet Spells at Winnipeg, Tech. Memoranda No. 630, Meteorological Branch, Canada Department of Transport, Toronto, 3 pp.

Slabbers, P.J., 1977, Surface Roughness of Crops and Potential Evapotranspiration, J. of Hydrology, 34:181-191.

Slabbers, P.J., V. S. Herrendorf and M. Stapper, 1979, Evaluation of Simplified Water-Crop Yield Models, Agr. Water Man. 93:93-129.

Sly, W.K. and J.C. Wilcox, 1976, Determining the Probable Starting Dates for Irrigating Perennial Crops, Can. Agr. Eng. 18:6-9.

Snedecor, G.W. and W.G. Cochran, 1980, Statistical Methods, Iowa State University Press, Ames, IA, 507 pp.

Sonmor, L.G., 1963, Seasonal Consumptive Use of Water by Crops Grown in Southern Alberta and Its Relationship to Evaporation, Can. J. Soil Sci. 43:287-297.

Staple, W.J., 1974, Modified Penman Equation to Provide the Upper Boundary Condition in Computing Evapotranspiration from Soil, Soil Sci. Soc. Amer. Proc. 38:837-839.

Statistics Branch, 1984, Agricultural Prices and Indices: June, July, and August, 1984, Alberta Agriculture, Edmonton.

Steed, G.L., R. Heywood and F. Davies, 1969, Irrigation Studies: Edmonton Region: Progress Report: 1968, Alberta Agriculture, Edmonton, various pagination.

Stegman, E.C. and A. Bauer, 1970, Computer Simulation Programming: An Aid to the Selection of Center Pivot Sprinkler Systems, Can. Agr. Eng. 12:92-97.

Stegman, E.C., D.T. Musick and J.I. Stewart, 1980, Irrigation Water Management, in: M.E. Jensen, ed., Design and Operation of Farm Irrigation Systems, ASAE, St. Joseph, MI, pp. 763-816.

Stewart, J.I. and R.M. Hagan, 1969, Predicting Effects of Water Shortage on Crop Yields, J. Irr. and Drain. Div, ASCE, 95:91-104.

Stewart, J.I., R.M. Hagan and W.O. Pruitt, 1974, Functions to Predict Optimal Irrigation Programs, J. Irr. and Drain. Div. ASCE 100:179-199.

Stewart, R. B., 1981, Modeling Methodology for Assessing Crop Production Potentials in Canada, Tech. Bull. 96, Agrometeorology Section, Land Resource Research Institute, Agriculture Canada, Ottawa, 29 pp.

Swaney, D.P., J.W. Jones, W.G. Boggess, G.G. Wilderson and J.W. Mishoe, 1983, Real-Time Irrigation Decision Analysis Using Simulation, Trans. ASAE 26:562-568.

Szeicz, G., G. Endroidi and S. Tajchman, 1969, Aerodynamic and Surface Factors in Evaporation, Water Resour. Res. 5:380-390.

Toogood, J.A., ed., 1963, Youngstown Irrigation Experiments, Department of Soil Science, University of Alberta, Edmonton, various pagination.

van Bavel, C.H.M, 1966, Potential Evaporation: The Combination Concept and Its Experimental Verification, Water Resour. Res. 2:455-467.

van Schaik, J.C., D.S. Chanasyk and E.H. Hobbs, 1976, An Assessment of the Capability of a Computer Program to Estimate Fall Soil Moisture and Deep Percolation, Can. J. Soil Sci. 56:357-362.

Verma, S.C. and H.R. Whitely, 1981, Simulating Irrigation Need from Climatological Records, ASAE NAR paper 81-419, 16 pp.

von Bernuth, R.D., D.L. Martin, J.R. Gilley and D.G. Watts, 1983, Irrigation System Capacities for Corn Production in Nebraska, ASAE paper 83-2005, 26 pp.

Wagner, H.M., 1975, Principles of Operations Research, Prentice Hall, Englewood Cliffs, N.J., 1039 pp.

Walker, D.R., 1973, Crop Production Potential in the Black and Grey Wooded Soil Zones of Alberta, in: Crop Production Potential in Alberta: Proceedings of the Alberta Soil Science Workshop, December, 1973, Alberta Agriculture, Edmonton, pp. 25-33.

Ward, R.C., 1975, Principles of Hydrology, McGraw-Hill Book Company, London, U.K., 367 pp.

Wilcox, 1963, The Effects of Weather on Evaporation from Bellani Plates and Evapotranspiration from Lysimeters, Can. J. Pl. Sci. 43:1-11.

Williams, G.D.V., 1969, Weather and Prairie Wheat Production, Can. J. Agr. Econ., 17:99-109.

Williams, G.D.V., 1974, Deriving a Biophotothermal Time Scale for Barley, Int. J. Biomet. 18:57-69.

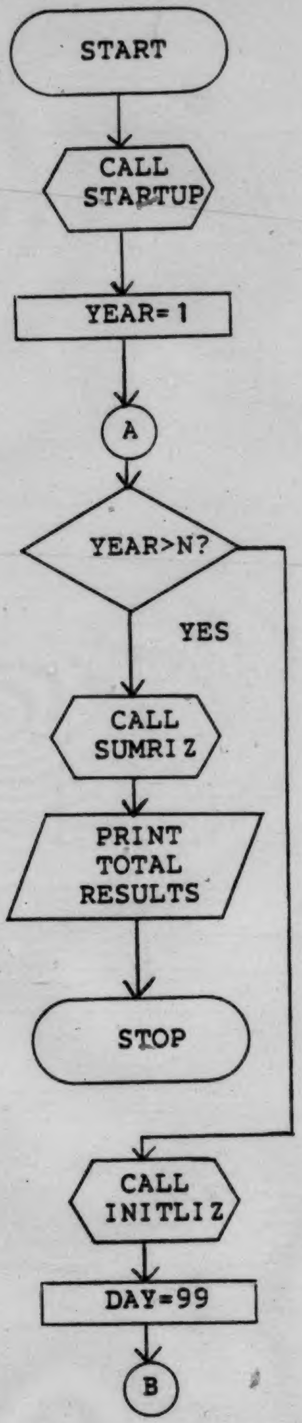
Windsor, J.S. and V. T. Chow, 1971, Model for Farm Irrigation in Humid Areas, J. Irr. Drain. Div. ASCE 97:369-385.

Wright, J.L. and M.E. Jensen, 1972, Peak Water Requirement of Crops Grown in Southern Idaho, J. Irr. and Drain. Div. ASCE 98:193-206.

Yang, S.J. and E. de Jong, 1972, Effect of Aerial Environment and Soil Water Potential on the Transpiration and Energy Status of Water in Wheat Plants, Agron. J. 64:574-578.

Yaron, D., G. Strateener, D. Shinurski and M. Weisbrood, 1973, Wheat Response and the Optimal Irrigation Policy Under Conditions of Unstable Rainfall, Water Resour. Res. 9:1145-1154.

Appendix A Program Flowchart


START
CALL STARTUP
YEAR=1
A
YEAR>N?
NO
YES
CALL SUMRIZ
PRINT TOTAL RESULTS
STOP
CALL INITLIZ
DAY=99
B

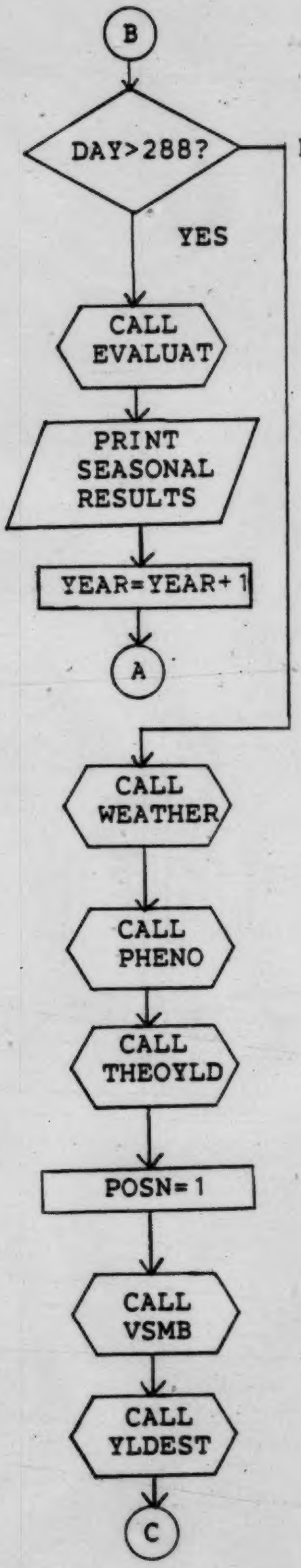
Read in parameters for the simulation run.

Have all seasons been simulated?

Summarize results for all seasons.

Initialize all variables at beginning of the season.

Start on April 9


B
DAY>288?
NO
YES
CALL EVALUAT
PRINT SEASONAL RESULTS
YEAR=YEAR+1
A
CALL WEATHER
CALL PHENO
CALL THEOYLD
POSN=1
CALL VSMB
CALL YLDEST
C

Reached October 16?

Evaluate that season's Performance.

Generate daily PET, precipitation, and temperatures.

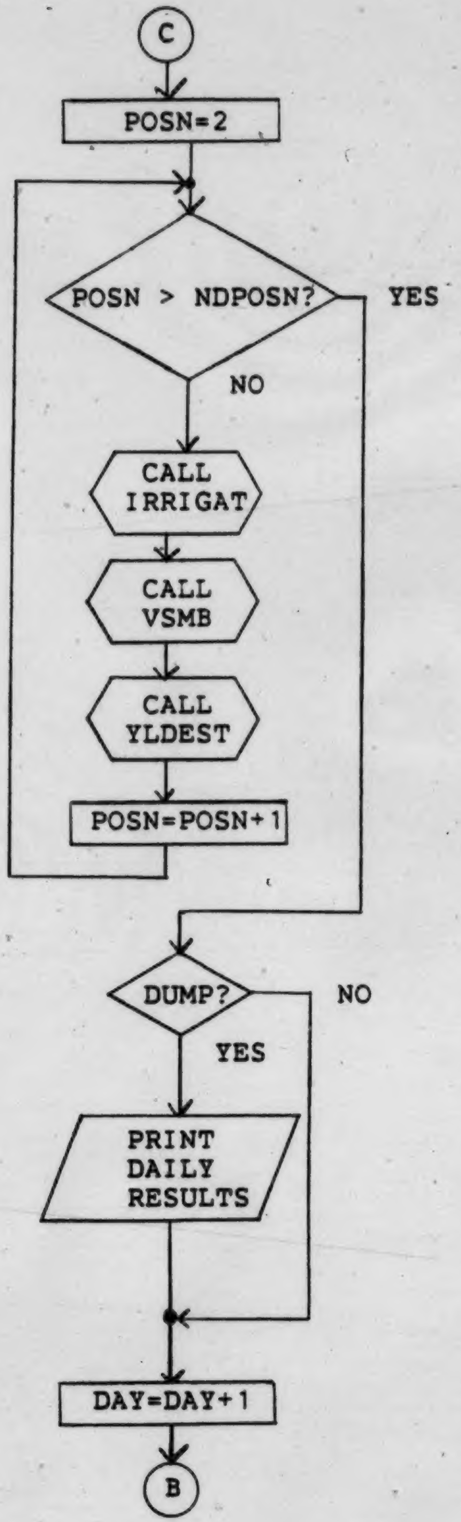
Estimate the phenological development of the crop.

Calculate the theoretical yield components common to dryland and irrigated crops.

Prepare to work through dryland area.

Calculate soil moisture and ET for dryland area.

Calculate yield for dryland area.


C
POSN=2
POSN > NDPOSN?
YES
NO
CALL IRRIGAT
CALL VSMB
CALL YLDEST
POSN=POSN+1
DUMP?
NO
YES
PRINT DAILY RESULTS
DAY=DAY+1
B

Prepare to work through irrigated area.

Completed all irrigated area?

Calculate how much, where, and when to irrigate.

Calculate soil moisture and ET for each irrigated position.

Calculate yield for each irrigated land area.

Dump daily results?

Appendix B Program Listing

```
R *PL1 SPRINT=-O,SPUNCH=-OBJ PAR=NA,NOL,NX,SIZE=04P,OPT=2
/*                                                               */
/* THE FOLLOWING IS A MODEL OF SOILS, WEATHER, CROPS (HARD       */
/* SPRING WHEAT AND ALFALFA HAY) AND IRRIGATION SYSTEMS         */
/* (SIDE ROLL, HARD HOSE REEL TRAVELER, AND TOWABLE AND STA-    */
/* TIONARY CENTRE PIVOTS).  THIS IS THE MODEL "APPEARS" TO BE   */
/* FUNCTIONALLY DEBUGGED -- BUT DON'T COUNT ON IT.  WARNING:    */
/* THERE IS NO ERROR CHECKING ON INPUT AND PL1 WON'T DO MUCH    */
/* CHECKING FOR YOU (EG. ACCESSING AN ARRAY OUT OF BOUNDS).     */
/* I TRIED TO DECLARE ALL VARIABLES EXPLICITLY -- IF A VARIABLE */
/* IS NOT DECLARED IN THE SUBPROGRAM LOOK IN THE CALLING        */
/* SUBPROGRAM OR IN IRRSIM.                                     */
/*                                                              */
/*      SOME NOTES FOR NOVICES TO INTERPRET PL1:                */
/* DCL -> DECLARE, FIXED -> INTEGER*2, FLOAT -> REAL*4,         */
/* BIT(1) -> LOGICAL, FLOAT DECIMAL(11) -> REAL*8, GET -> READ, */
/* PUT -> WRITE, ; -> END OF STATEMENT, | -> .OR., STATIC ->    */
/* HANG ONTO THE VALUE OF THIS VARIABLE BETWEEN INVOCATIONS OF  */
/* THE SUBPROGRAM, FLOOR -> TRUNCATE, CEIL -> INCREASE TO       */
/* INTEGER.                                                     */
/*                                                              */
/* IF YOU HAVE ANY QUESTIONS OR COMMENTS PLEASE FEEL FREE TO    */
/* CONTACT ME:                                                  */
/*                                                              */
/*     BRIAN MCCONKEY                                           */
/*     C/O                                                      */
/*     DEPARTMENT OF AGRICULTURAL ENGINEERING                   */
/*     RM 751 GENERAL SERVICES BUILDING                         */
/*     UNIVERSITY OF ALBERTA                                    */
/*     EDMONTON, AB                                             */
/*     T6G 2G6                                                  */
/*         PHONE (403) 432-4251                                 */
/*                                                              */
/*                                                              */
/****************************************************************/
/*                 IRRSIM                                       */
/*                                                              */
/*  IRRSIM IS THE MAIN PROGRAM AND CONTROLS THE SIMULATION      */
/*  IRRSIM ALSO CONTAINS MANY VARIABLES COMMON TO THE           */
/*  ENTIRE MODEL.                                               */
/*                                                              */
IRRSIM:PROCEDURE OPTIONS (MAIN);
                      /* SOIL MOISTURE-RELATED DATA GROUP       */
                      /* EACH INDEX RELATES TO ONE FIELD OR     */
                      /* PART OF FIELD                          */
DCL     (SM(4,6),     /* ACTUAL SOIL MOISTURE>WP (mm) IN EACH ZONE */
         AM(4,6),     /* AVAILABLE SOIL MOISTURE I.E. SM/(FC-WP)   */
                      /* IN EACH ZONE (FRACTION)                */
         ET(4),       /* DAILY ACTUAL ET (mm)                   */
         TOTET(4),    /* SIMULATION SEASON ET (mm)              */
         GSET(4),     /* GROWING SEASON ET (mm)                 */
         TOTRUNOFF(4),/* ACCUMULATED RUNOFF FOR WHOLE SEASON (mm)*/
         TOTDEEPERC(4))/* ACCUMULATED DEEP PERCOLATION FOR SEASON*/
           FLOAT;
                     /*     SOIL PHYSICS-RELATED DATA GROUP     */
                     /*                                         */
DCL    (SMC(6),      /* TOTAL AVAILABLE MOISTURE I.E. FC-WP (mm)  */
        SMSAT(6),    /* TOTAL SATURATED MOISTURE I.E. SAT-WP (mm) */
        PERCOEF(6),/* PERCOLATION COEFFICIENT FOR VSMB -- -       */
                     /* RANGES BETWEEN 0 (LIGHT & MEDIUM TEXTURED */
                  /* SOILS) & 1 (HEAVY TEXTURED SOILS)                  */
       TRACAM(3), /* AM FOR UPPER THREE ZONES BELOW WHICH               */
                  /* THE SOIL IS TRACTABLE                              */
       OPTMOIS(5),/* OPTIMUM DESIRED MOISTURE CONTENT                   */
                  /* IN THE ROOT ZONE (mm)                              */
       MINMOIS(5),/* MINIMUM DESIRED MOISTURE CONTENT                   */
                  /* IN THE ROOT ZONE (mm)                              */
       LDTLIM,    /* LOWEST EXPECTED AM ON APRIL 9 FOR DRYLAND          */
                  /* SOIL FOR THE TOP 1/8 OF THE ROOTING ZONE           */
       UDTLIM,    /* UPPERMOST EXPECTED AM FOR TOP 1/8 OF THE           */
                  /* ROOTING ZONE (AM CAN NOT > FIELD CAPACITY)         */
       LDBLIM,    /* LOWEST EXPECTED AM ON APRIL 9 FOR THE              */
                  /* BOTTOM 1/2 OF PROFILE, OTHERWISE LIKE              */
                  /* LDTLIM                                             */
       UDBLIM,    /* LIKE UDTLIM BUT FOR BOTTOM 1/2 OF SOIL             */
       LITLIM,    /*  "   LDTLIM  "   "  IRRIGATED SOIL                 */
       UITLIM,    /*  "   UDTLIM  "   "      "      "                   */
       LIBLIM,    /*  "   LDBLIM  "   "      "      "                   */
       UIBLIM,    /*  "   UDBLIM  "                                     */
       BOTPERM)   /* HYDRAULIC CONDUCTIVITY OF UNDERLYING               */
                  /* SOIL LAYER (mm/d)                                  */

        FLOAT,
       ROOTDEPTH(5) /* VSMB ZONES WITHIN ROOTZONE FOR                   */
                    /* EACH CROP GROWTH STAGE                           */

        FIXED;
DCL   DRY            /* POINTS TO UNIRRIGATED SOIL                      */
       FIXED INITIAL(1),
     (POSN,          /* POINTS TO POSITIONS ON                          */
                     /* IRRIGATED FIELD(S) I.E.                         */
                     /* POSN=2 : FIRST SET OR FIELD 1                   */
                     /* POSN=3 : MID SET OR FIELD 2                     */
                     /* POSN=4 : LAST SET OR FIELD 3                    */
      FIRSTSET,      /* NUMBER OF THE FIRST IRRIGATION SET              */
                     /* (USUALLY 1)                                     */
      MIDSET,        /* NUMBER OF THE MIDDLE IRRIGATION SET             */
      LASTSET,       /* NUMBER OF LAST IRRIGATION SET                   */
      NDPOSN,        /* LAST POSN TO BE CONSIDERED IN SIMULATION        */
      YEAR,          /* YEAR (I.E. SEASON) COUNTER                      */
      N,             /* NUMBER OF YEARS FOR SIMULATION                  */
      FIRSTDAY,      /* FIRST DAY IN SEASON IRRIGATION PERMITTED        */
      LASTDAY,       /* LAST DAY IN SEASON IRRIGTIO PERMITTED           */
      DELAY,         /* NUMBER OF DAYS IRRIGATION IS DELAYED            */
                     /* FOR A MULTIPLE SET SYSTEM                       */
      WHEREIS,       /* INDICATES WHERE THE IRRIGATION SYSTEM IS        */
                     /* PRESENTLY                                       */
      IRRTYPE,       /* IRRIGATION SYSTEM TYPE: 1=CENTRE PIVOT          */
                     /* 2=SIDE ROLL 3=HARD HOSE TRAVELER                */
      INDYRS,        /* CODE WHICH TELLS MODEL WHETHER TO OUTPUT        */
                     /* COMPLETE RESULTS FOR INDIVIDUAL YEARS           */
                     /*   0 -> NO OUTPUT, 1 -> OUTPUT                   */
      SOILTYPE,      /* CODE INDICATING GENERAL SOIL TYPE               */
      I,J)FIXED;     /* COUNTERS                                        */
 DCL (LAT,           /* LATITUDE OF AREA (DEGREES)                      */
      IRR(4),        /* DAILY AMOUNT OF IRRIGATION (mm) FOR EACH        */
                     /* SOIL AREA                                       */
      IRREFF,        /* IRRIGATION EFFICIENCY (FRACTION)                */
      SYSRAT,        /* IRRIGATION SYSTEM APPLICATION RATE (mm/h)       */
                     /* FOR CENTRE PIVOT-> ha-mm/d (10m**3/d)           */
      IRRAREA,       /* ha IRRIGATED EACH DAY                           */
      IRRH2O,        /* DAILY NET IRRIGATION APPLICATION (mm/ha)        */
      TOTH2O,        /* ACCUMULATED  IRRIGATION (ha-mm)           */
      TOTIREA,       /* ACCUMULATED IRRIGATED AREA (ha)           */
      IRRLAB,        /* ACCUMULATED NET LABOUR (h) ESTIMATE       */
      SETAREA,       /* AREA IRRIGATED EACH SET (ha)              */
      MAXRATE,       /* MAXIMUM IRRIGATION SYSTEM RATE            */
                     /* CENTRE PIVOT -> REVOLUTIONS/d             */
                     /* SIDE ROLL AND HARD HOSE TRAVELER ->       */
                     /*          MAXIMUM NUMBER OF SETS/d         */
      MINRATE,       /* LIKE MAXRATE EXCEPT MIMIMUMS              */
      RESERV,        /* MAXIMUM QUANTITY OF WATER AVAILABLE FOR   */
                     /* IRRIGATION (ha-mm NET)                    */
      MAXAPP,        /* MAXIMUM NET APPLICATION POSSIBLE OVER THE */
                     /* YEAR DUE TO MOISTURE LIMITATIONS (mm)     */
      IRRAIN,        /* ACCUMULATED RAINFALL SINCE A IRRIGATION   */
                     /* BEGAN                                     */
      STATUS,        /* LOCATION OF IRRIGATION SYSTEM (SET.FRAC)  */
      MOVTIM)        /* TIME REQUIRED TO MOVE BETWEEN SETS (h)    */
       FLOAT ;
 DCL (ANFXCST,       /* ANNUAL COST OF IRRIGATION SYSTEM +        */
                     /* MAINTENANCE $/YR                          */
      FIXDCOST,      /* ANNUAL COST $/ha                          */
      FERTCOST,      /* COST OF EXTRA FERTILIZER NEEDED FOR IRR-  */
                     /* IGATED PRODUCTION $/ha                    */
      HARVCOST,      /* APPROXIMATED ESTIMATED COST OF HARVESTING */
                     /* CROP $/kg                                 */
      FLDSIZ,        /* TOTAL AREA OF ALL IRRIGATED LAND (ha)     */
      LABRAT,        /* LABOUR COST $/mm/ha                       */
      NRGRAT,        /* ENERGY COST $/mm/ha                       */
      HEADRAT,       /* PUMPING COST TO BRING WATER TO FIELD      */
                     /* LEVEL $/mm/ha/m OF EXTRA DYNAMIC HEAD     */
      XTRAHEAD,      /* M OF EXTRA HEAD TO BRING WATER TO FIELD   */
      CROPVAL)       /* VALUE OF CROP $/kg                        */
       FLOAT;
                     /*                                           */
                     /*    KEY DAYS DURING SEASON                 */
                     /*                                           */
 DCL (DAY,           /* DAY OF YEAR EG. JAN 1=1                   */
      BEGDAY,        /* FIRST DAY OF ACTIVE GROWING SEASON ->     */
                     /*  WHEAT: DAY OF SEEDING                    */
                     /*  ALFALFA: DAY GROWTH STARTS IN SPRING     */
      ENDDAY,        /* LAST DAY OF ACTIVE GROWING SEASON         */
      FCDAY,         /* DAY OF FIRST CUT (ALFALFA)                */
      SCDAY,         /* DAY OF SECOND CUT (ALFALFA)               */
      GSDAYS,        /* LENGTH OF ACTUAL GROWING SEASON           */
      GADAYS(3),     /* DAYS IN EACH ALFALFA GROWTH PERIOD        */
      SEEDDAYS,      /* DAYS OF SEEDING WHEAT                     */
      IRRDAYS,       /* DAYS SPENT IRRIGATING                     */
      LOCN,          /* LOCATION CODE:                            */
                     /*    1 -> CORONATION                        */
                     /*    2 -> EDMONTON                          */
                     /*    3 -> LACOMBE                           */
                     /*    4 -> LETHBRIDGE                        */
      NIP,           /* NUMBER OF IRRIGATED POSITIONS             */
      NUMIRR)        /* TOTAL NUMBER OF IRRIGATIONS               */
       FIXED;
                     /*                                           */
                     /*    WEATHER-RELATED DATA GROUP             */
                     /*                                           */
 DCL  (RAIN,         /* DAILY PRECIPITATION (mm)                  */
      TOTRAIN,       /* SIMULATION SEASON PRECIPITATION (mm)      */
      GSRAIN,       /* GROWING SEASON PRECIPITATION                 */
      TMAX,         /* DAILY MAXIMUM TEMPERATURE (C)                */
      TMIN,         /* DAILY MINIMUM TEMPERATURE (C)                */
      TX,           /* TMAX (F)                                     */
      TN,           /* TMIN (F)                                     */
      DAYLEN,       /* LENGTH OF DAY IN HOURS                       */
      LE,           /* BAIER AND ROBERTSON'S ESTIMATE OF            */
                    /* LATENT EVAPORATION FROM A BLACK BELANI       */
                    /* PLATE ATOMETER (mL/d)                        */
      XTERAD,       /* EXTRATERRESTIAL SOLAR RADIATION              */
                    /* (W/m**2)                                     */
      XT,           /* XTERAD IN cal/cm**2/d                        */
      TMEAN,        /* DAILY MEAN TEMPERATURE (C)                   */
      PET,          /* DAILY POTENTIAL ET (mm)                      */
      TOTPET,       /* SIMULATION SEASON PET (mm)                   */
      GSPET,        /* GROWING SEASON PET (mm)                      */
      DEGDAYS,      /* DEGREE DAYS ABOVE 5.0 C                      */
      GSDD,         /* DEGREE DAYS DURING ACTIVE GROWING            */
      DRYPET)       /* AVERAGE EXPECTED DRY DAY PET                 */
        FLOAT;
                      /*                                            */
                      /* WEATHER PROBABILITY RELATED                */
                      /* DATA GROUP                                 */
                      /*                                            */
DCL (AVGTMAX(19,0:1), /* AVERAGE TMAX FOR EACH 10 DAY PERIOD        */
                      /* ON WET AND DRY DAYS                        */
     SDTMAX(19,0:1),  /* STANDARD DEVIATION OF TMAX FOR EACH        */
                      /* 10 DAY PERIOD ON WET AN DRY DAYS           */
     ATNTX(19,0:1),   /* REGRESSION INTERCEPT FOR TMIN AS A         */
                      /* LINEAR FUNCTION OF TMAX                    */
     BTNTX(19,0:1),   /* SLOPE OF TMIN VS TMAX                      */
     SDTNTX(19,0:1),  /* STANDARD ERROR OF TMIN VS TMAX             */
     APETX(19,0:1),   /* INTERCEPT OF PET VS TMAX                   */
     BPETX(19,0:1),   /* SLOPE OF PET VS TMAX                       */
     SDPETX(19,0:1),  /* STANDARD ERROR OF PET VS TMAX              */
     AVGRAIN(19),     /* AVERAGE OF THE CUBE ROOT OF RAIN ON        */
                      /* RAINY DAYS FOR EACH 10 DAY PERIOD          */
     SDRAIN(19),      /* STANDARD DEVIATION OF THE CUBE ROOT OF*/
                      /* RAINFALL ON RAINY DAYS FOR EACH PERIOD*/
     PWD(19),         /* PROBABILITY OF A WET DAY FOLLOWING A       */
                      /* DRY DAY FOR EACH 10 DAY PERIOD             */
     PWW(19))         /* PROBABILITY OF A WET DAY FOLLOWING         */
                      /* A WET DAY FOR EACH 10 DAY PERIOD           */
      FLOAT;
DCL (SEEDNUM,         /* SEED NUMBER FOR RANDOM # GENERATOR         */
                      /* MUST BETWEEN 0 AND 199017                  */
     INITSEED)        /* SEED NUMBER AT START OF SEASON             */
      FLOAT DECIMAL(11);
DCL  WET              /* WET=0 -> DRY DAY                           */
      FIXED;          /* WET=1 -> WET DAY                           */
DCL (DRYBEGSM,        /* MOISTURE IN TOTAL ROOT DEPTH OF DRY        */
                      /* SOIL ON APRIL 9                            */
     IRRBEGSM,        /* MOISTURE IN TOTAL ROOT DEPTH OF IRRI-      */
                      /* GATED SOIL ON APRIL 9                      */
     DRYENDSM,        /* MOISTURE IN TOTAL ROOT DEPTH ON            */
                      /* OCT 15 FOR DRYLAND                         */
     IRRENDSM)        /* OCT 15 SOIL MOISTURE FOR IRRIGATED         */
      FLOAT;
DCL TRUE BIT(1) INITIAL('1'B);
DCL FALSE BIT(1) INITIAL('0'B);
DCL    (GROWING,        /* IS CROP GROWING FLAG                       */
        EOSEAS,         /* IS SEASON OVER FLAG                        */
        DUMP,           /* SHOULD DAILY DATA BE DUMPED OUT            */
        IDLE)           /* FLAG INDICATING IF IRRIGATION SYSTEM IS    */
                        /* BUSY                                       */
              BIT(1) ;
                        /*                                            */
                        /*         CROP-RELATED DATA GROUP            */
                        /*                                            */
DCL    (CROP,           /* CROP=1 : WHEAT                             */
                        /* CROP=2 : ALFALFA                           */
        YLDMETH,        /* METHOD FOR DETERMINING YIELD               */
                        /*  1 -> SIMFOY                               */
                        /*  2 -> WAGENINGEN (ALWAYS FOR WHEAT)        */
        LIFESTAGE,      /* STAGE IN CROP DEVELOPMENT  I.E.            */
                        /*  WHEAT :                                   */
                        /*    1=PLANTING TO EMERGENCE                 */
                        /*    2=EMERGENCE TO JOINTING                 */
                        /*    3=JOINTING TO HEADING                   */
                        /*    4=HEADING TO SOFT DOUGH                 */
                        /*    5=SOFT DOUGH TO RIPENING                */
                        /*  ALFALFA:                                  */
                        /*    1=START OF GROWTH TO FULL COVER         */
                        /*    2=FULL COVER TO FIRST CUT               */
                        /*    3=FIRST CUT TO FULL COVER               */
                        /*    4=FULL COVER TO SECOND CUT              */
                        /*    5=AFTER SECOND CUT                      */
         GROWTH)        /* GROWTH PERIOD OF ALFALFA 1,2 OR 3          */
         FIXED,
       (PHENOSTAGE,     /* PHENOLOGICAL STAGE IN CROP DEVELOPMENT     */
        D,              /* INDICATES RELATIVE DEVELOPMENT OF          */
                        /* ALFALFA BETWEEN START OF (RE)GROWTH        */
                        /* AND HARVESTING D=0.0 AT START OF           */
                        /* OF (RE)GROWTH D=1.0 AT HARVEST             */
        TOPPOR(4))      /* PROPORTION OF TOTAL ALFALFA GROWTH WHICH   */
                        /* IS HARVESTED I.E. MINUS ROOT GROWTH        */
         FLOAT;
                        /* YIELD INFORMATION FOR EACH POSITION        */
DCL    (YIELD(4),       /* CUMULATIVE ACTUAL GROWTH (kg/ha)           */
                        /*  WHEAT -> GRAIN @ 14.5% m.c.               */
                        /*  ALFALFA (SIMFOY) -> HAY @ 15% M. C.       */
                        /*          (WAGENINGEN) -> HAY @ 15%         */
        AFYLDS(4,3),    /* ALFALFA YIELDS FOR FIRST, SECOND AND       */
                        /* THIRD GROWTHS (kg/ha)                      */
        MNGFAC,         /* FACTOR WHICH TAKES INTO ACCOUNT THE        */
                        /* EFFECT OF MANAGEMENT ON CROP YIELD         */
        AWMSF(4),       /* ACCUMULATED MOISTURE STRESS FACTOR FOR     */
                        /* WHEAT IN EACH POSN                         */
        WMSF(4))        /* MOISTURE STRESS FACTOR FOR EACH POSN       */
         FLOAT;
DCL     IRRGTNS(30,3)   /* CONTAINS DATE IRRIGATION WAS STARTED,      */
                        /* THE NET AMOUNT OF THAT IRRIGATION, AND     */
                        /* (FOR TOWABLE PIVOTS) THE FIELD WHICH       */
                        /* WAS IRRIGATED                              */
         FLOAT;
                        /* POTENTIAL YIELD DATA GROUP WHERE MOISTURE*/
                        /* IS NOT LIMITING.  THIS IS THE SAME FOR     */
                        /* ALL SOILS                                  */
DCL    (YPOT,           /* POTENTIAL DAILY YIELD (kg/ha)              */
        POTYIELD,       /* CUMULATIVE POTENTIAL YIELD (kg/ha)         */
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          POTAFYLDS(3))/*POTENTIAL ALFALFA YIELDS FOR FIRST,        */
                       /* SECOND, AND THIRD GROWTHS (kg/ha)         */
            FLOAT;                                                  */
DCL (SUMSM(2),         /* SUM OF ANNUAL BEGINING SOIL MOISTURE      */
                       /*  1 -> DRY                                 */
                       /*  2 -> IRRIGATED                           */
     SUMRUN(2),        /* SUM OF ANNUAL SURFACE RUNOFF              */
     SUMPERC(2),       /*  "   "     "   DEEP PERCOLATION           */
     SUMET(2),         /*  "   "     "   GROWING SEASON ET          */
     SUMRET(2),        /*  "   "     "   ET/PET FOR GROWING SEASON  */
     SUMTET(2),        /*  "   "     "   TOTAL ET                   */
     SUMYLD(2),        /*  "   "     "   YIELDS                     */
     SUMCUT1(2),       /*  "   "     "   FIRST ALFALFA CUTS         */
     SUMCUT2(2))       /*  "   "     "   SECOND ALFALFA CUTS        */
       FLOAT INITIAL((18)0.0);
DCL (SUMINC,           /*  "   "     "   YIELD INCREASES            */
     SUMNET,           /*  "   "     "   NET DEPTH OF APPLICATION   */
     SUMNMIRR,         /*  "   "     "   NUMBER OF IRRIGATIONS      */
     SUMLAB,           /*  "   "     "   IRRIGATION LABOUR          */
     SUMVAR,           /*  "   "     "   IRRIGATION VARIABLE COSTS  */
     SUMPRF)           /*  "   "     "   PROFITS FROM IRRIGATION    */
       FLOAT INITIAL(0.0);
DCL (SSQSM(2),         /* SUM OF SQUARES OF ANNUAL SPRING MOISTURE*/
     SSQRUN(2),        /*  "   "     "     "   "   TOTAL RUNOFF    */
     SSQPERC(2),       /*  "   "     "     "   "   PERCOLATION     */
     SSQET(2),         /*  "   "     "     "   "   GROWING ET      */
     SSQRET(2),        /*  "   "     "     "   "   ET/PET          */
     SSQTET(2),        /*  "   "     "     "   "   TOTAL ET        */
     SSQYLD(2),        /*  "   "     "     "   "   YIELDS          */
     SSQCUT1(2),       /*  "   "     "     "   "   FIRST CUT       */
     SSQCUT2(2))       /*  "   "     "     "   "   SECOND CUT      */
       FLOAT INITIAL((18)0.0);
DCL (SSQINC,           /*  "   "     "     "   "   YIELD INCREASE  */
     SSQNET,           /*  "   "     "     "   "   NET DEPTH       */
     SSQNMIRR,         /*  "   "     "     "   "   IRRIGATIONS     */
     SSQLAB,           /*  "   "     "     "   "   LABOUR          */
     SSQVAR,           /*  "   "     "     "   "   VARIABLE COSTS  */
     SSQPRF)           /*  "   "     "     "   "   PROFITS         */
       FLOAT INITIAL(0.0);
DCL WHEAT FIXED INITIAL(1);
DCL ALFALFA FIXED INITIAL(2);
DCL NAME(2) CHARACTER(7) INITIAL('WHEAT  ','ALFALFA');
DCL METHOD(2) CHARACTER(17) INITIAL('SIMFOY METHOD',
                                    'WAGENINGEN METHOD');

DCL OUT FILE PRINT;
OPEN FILE(OUT);
DCL OYR FILE PRINT;
OPEN FILE(OYR);                                                     */
/*                                                                  */
/*******************************************************************/
/*                                                                  */
/*                     START SIMULATION                             */
/*                                                                  */
CALL STARTUP;          /* READ IN PARAMETERS FOR ENTIRE SIMULATION*/
/*                                                                  */
LIFETIME:DO YEAR=1 TO N;  /* INITIALIZE AT THE START OF EACH YEAR*/
  CALL INITLIZ;                                                     */
  /*                                                                */
  /* START A SIMULATION SEASON                                      */
  /*
  SEASON:DO DAY=99 TO 288;             /* APRIL 9 TO OCTOBER 15 */
    CALL WEATHER;                /* GENERATE THIS DAY'S WEATHER */
    CALL PHENO;                /* ESTIMATE GROWTH STAGE OF CROP */
    POSN=DRY;
    CALL VSMB;
    IF ¬GROWING THEN GOTO IRRFLD;
    CALL THEOYLD;  /* ESTIMATE YIELD WHEN MOISTURE NOT LIMITING */
    CALL YLDEST;   /* ESTIMATE DRYLAND YIELDS                   */
    /*                                                          */
    /* SIMULATE OVER IRRIGATED FIELD(S)                         */
    /*                                                          */
    IRRFLD:DO POSN=2 TO NDPOSN;
      IF GROWING THEN CALL IRRIGAT; /* DETERMINE HOW MUCH, WHEN */
                                    /* AND WHERE TO IRRIGATE    */
      CALL VSMB;
      IF GROWING THEN CALL YLDEST;  /* ESTIMATE IRRIGATED YIELDS*/
    END IRRFLD;
    IF DUMP THEN CALL DAYOUT;      /* DUMP OUT DAILY INFORMATION*/
    /*                                                          */
    /* RESET SOME IRRIGATION VARIABLES                          */
    /*                                                          */
    DO I=1 TO NDPOSN;  IRR(I)=0.0;   END;
    IRRH2O=0.0;
    IRRAREA=0.0;
  END SEASON;
  CALL EVALUAT;     /* EVALUATE AND OUTPUT SEASONAL PERFORMANCE */
END LIFETIME;
CALL SUMRIZ;        /*   SUMARIZE PERFORMANCE OVER MANY SEASONS */
/*                                                              */
/****************************************************************/
/*                                                              */
/*                      END SIMULATION                          */
/*                                                              */
/****************************************************************/
/*                                                              */
/*                 STARTUP                                      */
/*                                                              */
/*  STARTUP READS IN PARAMETERS FOR THE SIMULATION              */
/*                                                              */
STARTUP:PROCEDURE;
DCL LOCATION(4) CHARACTER(10) INITIAL('CORONATION',
           'EDMONTON','LACOMBE','LETHBRIDGE');
DCL STYP(3) CHARACTER(3) INITIAL('I  ','II ','III');
DCL ITYP(3) CHARACTER(18) INITIAL('CENTRE PIVOT',
           'SIDE ROLL','HARD HOSE TRAVELER');
DCL RAM FLOAT;  /* ROOT ZONE AM mm                              */
DCL SOIL FILE INPUT STREAM;
DCL IRR FILE INPUT STREAM;
DCL INFO FILE INPUT STREAM;
DCL PR FILE INPUT STREAM;
DCL FPET FILE INPUT ENVIRONMENT(U(132));
DCL CRITW FILE INPUT STREAM;
DCL CRITA FILE INPUT STREAM;
OPEN FILE(CRITW);
OPEN FILE(CRITA);
OPEN FILE(WSOIL);
OPEN FILE(ASOIL);
OPEN FILE(IRR);
OPEN FILE(INFO);
OPEN FILE(PR);
OPEN FILE(FPET);
GET FILE (INFO) LIST(CROP,CROPVAL,YLDMETH,HARVCOST,MNGFAC,
                     FIRSTDAY,LASTDAY,N,SEEDNUM,INDYRS);
IF CROP = 1 THEN    /* WHEAT */
  DO;
    GET FILE(WSOIL) LIST(SOILTYPE,(SMC(I) DO I=1 TO 6),
     (SMSAT(I) DO I=1 TO 6),
     (PERCOEF(I) DO I=1 TO 6),(ROOTDEPTH(I) DO I=1 TO 5),
     (TRACAM(I) DO I=1 TO 3),BOTPERM);
    GET FILE(CRITW) LIST((MINMOIS(I) DO I=1 TO 5),
                         (OPTMOIS(I) DO I=1 TO 5),LDTLIM,UDTLIM,
          LDBLIM,UDBLIM,LITLIM,UITLIM,LIBLIM,UIBLIM,FERTCOST);
  END;
          ELSE    /* ALFALFA  */
  DO;
    GET FILE(ASOIL) LIST(SOILTYPE,(SMC(I) DO I=1 TO 6),
          (SMSAT(I) DO I=1 TO 6),
       (PERCOEF(I) DO I=1 TO 6),(ROOTDEPTH(I) DO I=1 TO 5),
      (TRACAM(I) DO I=1 TO 3),BOTPERM);
    GET FILE(CRITA) LIST((MINMOIS(I) DO I=1 TO 5),
                         (OPTMOIS(I) DO I=1 TO 5),LDTLIM,UDTLIM,
          LDBLIM,UDBLIM,LITLIM,UITLIM,LIBLIM,UIBLIM,FERTCOST);
  END;
 GET FILE (IRR) LIST(IRRTYPE,NDPOSN,MAXAPP,SETAREA,SYSRAT,IRREFF,
                     MINRATE,MAXRATE,MOVTIM,
                     FIRSTSET,MIDSET,LASTSET,ANFXCST,LABRAT,
                     NRGRAT,HEADRAT,XTRAHEAD);
 GET FILE(PR) LIST(LOCN,LAT);
 DO I=1 TO 19;
   GET FILE(PR) LIST(AVGRAIN(I),SDRAIN(I),PWD(I),PWW(I));
 END;
 DO I=1 TO 19;
   DO J=0 TO 1;
      GET FILE(FPET) LIST(AVGTMAX(I,J),SDTMAX(I,J),ATNTX(I,J),
        BTNTX(I,J),SDTNTX(I,J),APETX(I,J),BPETX(I,J),SDPETX(I,J));
   END;
 END;
 CLOSE FILE(ASOIL);
 CLOSE FILE(CRITW);
 CLOSE FILE(CRITA);
 CLOSE FILE(WSOIL);
 CLOSE FILE(IRR);
 CLOSE FILE(INFO);
 CLOSE FILE(PR);
 CLOSE FILE(FPET);
 DUMP=FALSE;
 INITSEED=SEEDNUM;
 NIP=NDPOSN-1;
 IF IRRTYPE=1 THEN  /* CENTRE PIVOT                           */
   FLDSIZ=SETAREA*NIP;                                        */
             ELSE  /* MULTIPLE SET
   FLDSIZ=SETAREA*LASTSET;
 FIXDCOST=ANFXCST/FLDSIZ;
 IF CROP = WHEAT THEN YLDMETH=2;                              */
 /*                                                           */
 /* PRINT OUT SIMULATION PARAMETERS                           */
 /*
 PUT SKIP FILE(OUT) EDIT('SUMMARY')(COL(30),A);
 PUT SKIP(0) FILE(OUT) EDIT((7)'_')(COL(30),A);
 PUT SKIP(3) FILE(OUT) EDIT('LOCATION=',LOCATION(LOCN),
                          'SOIL TYPE= ',STYP(SOILTYPE))
       (COL(5),A,A(10),COL(45),A,A(3));
PUT SKIP(2) FILE(OUT) EDIT('CROP=',NAME(CROP),' @ $',
                          (CROPVAL*1000.0),'/t',
                          'MANAGEMENT FACTOR= ',MNGFAC)
                  (COL(5),A,A(7),A,F(6,2),A,COL(45),A,F(4,2));
IF CROP = ALFALFA THEN
  PUT SKIP FILE(OUT) EDIT('YIELD ESTIMATION BY ',
                         METHOD(YLDMETH))(COL(10),A,A(17));
PUT SKIP(2) FILE(OUT) EDIT('SPRING STARTING AVAILABLE MOISTURE',
'    TOP    ','  BOTTOM ')(COL(5),A,COL(40),A,COL(60),A);
PUT SKIP FILE(OUT) EDIT('DRYLAND:',LDTLIM,'-',UDTLIM,
                      LDBLIM,'-',UDBLIM)
     (COL(10),A,COL(40),F(4,2),A,F(4,2),COL(60),F(4,2),A,F(4,2));
PUT SKIP FILE(OUT) EDIT('IRRIGATED:',LITLIM,'-',UITLIM,
                      LIBLIM,'-',UIBLIM)
     (COL(10),A,COL(40),F(4,2),A,F(4,2),COL(60),F(4,2),A,F(4,2));
PUT SKIP(2) FILE(OUT) EDIT('IRRIGATED AREA=',FLDSIZ,' ha',
                         'SET AREA=',SETAREA,' ha')
                         (COL(5),A,F(6,1),A,COL(45),A,F(6,2),A);
PUT SKIP FILE(OUT) EDIT('WATER SUPPLY FOR SEASON=',
                        (MAXAPP*FLDSIZ/IRREFF),
                        ' ha-mm','MAXIMUM TOTAL NET IRRIGATION=',
                        MAXAPP,' mm')
                        (COL(5),A,F(7,0),A,COL(15),A,F(5,0),A);
IF IRRTYPE = 1 THEN  /* CENTRE PIVOT */
  DO;
    PUT SKIP(2) FILE(OUT) EDIT('CENTRE PIVOT','CAPACITY=',
                         (SYSRAT*0.115741/IRREFF),' L/s (GROSS)')
                            (COL(5),A,COL(45),A,F(6,1),A);
    PUT SKIP FILE(OUT) EDIT('MINIMUM REVOLUTIONS/d=',MINRATE,
                           'MAXIMUM REVOLUTIONS/d=',MAXRATE)
                           (COL(5),A,F(5,2),COL(45),A,F(5,2));
  END;
               ELSE  /* MULTIPLE SET SYSTEM  */
  DO;
    PUT SKIP(2) FILE(OUT) EDIT(ITYP(IRRTYPE),'CAPACITY=',
                               SYSRAT,' mm/h (NET)')
                               (COL(5),A(18),COL(45),A,F(5,1),A);
    PUT SKIP FILE(OUT) EDIT('INTER SET MOVING TIME=',MOVTIM,
                           ' h','SETS/d: MAX= ',MAXRATE,
                           '  MIN= ',MINRATE)
                    (COL(5),A,F(4,2),A,COL(45),A,F(3,1),A,F(3,1));
  END;
PUT SKIP(2) FILE(OUT) EDIT('NO IRRIGATION BEFORE DAY = ',FIRSTDAY,
                           'OR AFTER DAY = ',LASTDAY)
                           (X(5),A,F(3,0),X(1),A,F(3,0));
PUT SKIP(3) FILE(OUT) EDIT('IRRIGATION CRITERIA:')(COL(40),A);
PUT SKIP FILE(OUT) EDIT('LIFESTAGE','ROOT ZONE AM (mm)',
                        'MINIMUM AM (mm)','OPTIMUM AM (mm)')
                       (X(1),A,COL(15),A,COL(35),A,COL(53),A);
DO L=1 TO 5;
  RAM=0.0;
  DO J=1 TO ROOTDEPTH(L);
    RAM=RAM+SMC(J);
  END;
  PUT SKIP FILE(OUT) EDIT(L,RAM,MINMOIS(L),OPTMOIS(L))
      (X(5),F(1,0),COL(20),F(3,0),COL(39),F(3,0),COL(59),F(3,0));
END;
PUT SKIP(3) FILE(OUT) EDIT('FIXED SYSTEM COSTS= $',FIXDCOST,
             '/ha','FERTILIZER COSTS= $',FERTCOST,'/ha')
            (COL(5),A,F(6,2),A,COL(45),A,F(6,2),A);
PUT SKIP FILE(OUT) EDIT('VARIABLE COSTS= $',
                  (HEADRAT*XTRAHEAD+LABRAT+NRGRAT),
                  '/ha-mm','HARVESTING COSTS= $',
                   (HARVCOST*1000.0),'/t')
                  (COL(5),A,F(6,4),A,COL(45),A,F(5,2),A);
PUT SKIP(2) FILE(OUT) EDIT('SEED NUMBER=',INITSEED)
                        (COL(10),A,F(7,0));
PUT SKIP FILE(OUT); PUT SKIP FILE(OUT); PUT SKIP FILE(OUT);
IF CROP = WHEAT THEN
  DO;
    PUT SKIP FILE(OUT) EDIT('DRYLAND','IRRIGATED')
                         (COL(21),A,COL(43),A);
    PUT SKIP FILE(OUT) EDIT('    YR  RAIN  SSM    ET ',
         ' YIELD  SSM   IRR   #   ET  YIELD',
         '  VCOST  PROFIT')(A,A,A);
    PUT SKIP FILE(OUT) EDIT('             mm    mm    mm ',
         ' kg/ha   mm    mm        mm  kg/ha',
         '    $/ha   $/ha ')(A,A,A);
    PUT SKIP(0) FILE(OUT) EDIT((70)'_')(X(2),A);
    PUT SKIP FILE(OUT); PUT SKIP FILE(OUT);
  END;
             ELSE /* ALFALFA */
  DO;
    PUT SKIP FILE(OUT) EDIT('DRYLAND','IRRIGATED')
                         (COL(20),A,COL(40),A);
    PUT SKIP FILE(OUT) EDIT('  YR RAIN SSM  ET YIELD(kg/ha) SSM ',
         'IRR   #  ET  YIELD(kg/ha)  VCOST  PROFIT')(A,A);
    PUT SKIP FILE(OUT) EDIT('       mm   mm  mm  CUT1  CUT2   mm ',
         ' mm       mm   CUT1  CUT2    $/ha   $/ha ')
         (A,A);
    PUT SKIP(0) FILE(OUT) EDIT((72)'_')(X(2),A);
    PUT SKIP FILE(OUT); PUT SKIP FILE(OUT);
  END;
END STARTUP;
/*                                                        */
/***************END OF STARTUP*****************************/
/*                                                        */
/**********************************************************/
/*                                                        */
/*               INITLIZ                                  */
/*                                                        */
/*  INITLIZ HANDLES ALL INITIALIZATION AT THE START OF EACH */
/*  SEASON                                                */
/*                                                        */
INITLIZ:PROCEDURE;
DCL (MOIS,     /* SPRING STARTING MOISTURE FOR EACH ZONE (mm)  */
    BEGMR(6)) /* AM ON APRIL 9 FOR EACH SOIL ZONE              */
    FLOAT;
INITSEED=SEEDNUM;
WET=0; /* START OF WITH APRIL 8 BEING DRY                      */
TOTRAIN=0.0;
GSRAIN=0.0;
TOTPET=0.0;
GSPET=0.0;
IF INDYRS > 0 THEN DUMP=TRUE;
GROWING=FALSE;
LIFESTAGE=1;
PHENOSTAGE=0.0;
```

```
D=0.0;
GROWTH=1;
DO I=1 TO NDPOSN;
  IRR(I)=0.0;
  YIELD(I)=0.0;
  WMSF(I)=1.0;
  AWMSF(I)=0.0;
  TOPPOR(I)=1.0;
  TOTRUNOFF(I)=0.0;
  TOTDEEPERC(I)=0.0;
  GSET(I)=0.0;
  TOTET(I)=0.0;
  DO J= 1 TO 3;
    GADAYS(J)=0;
    AFYLDS(I,J)=0.0;
    POTAFYLDS(J)=0.0;
  END;
END;
POTYIELD=0.0;
IRRAREA=0.0;
IRRH2O=0.0;
RESERV=MAXAPP*FLDSIZ/IRREFF;
NUMIRR=0;
IRRDAYS=0;
TOTH2O=0.0;
TOTIREA=0.0;
IRRLAB=0.0;
EOSEAS=FALSE;
BEGDAY=999;
GSDAYS=0;
IDLE=TRUE;     /*IRRIGATION SYSTEM STARTS THE SEASON IDLE         */
STATUS=0.0;
IRRAIN=0.0;
WHEREIS=2;     /*IRRIGATION SYSTEM STARTS OFF IN POSN 2           */
               /* I.E. STARTING POSITION OR FIELD 1               */

DELAY=0;
SEEDDAYS=0;
ENDDAY=999;
FCDAY=999;
SCDAY=999;
DEGDAYS=0.0;
GSDD=0.0;                                                          */
/*                                                                 */
/* ESTIMATE SPRING STARTING MOISTURE FOR DRYLAND SOIL. ASSUME      */
/* SOIL CAN NOT BE ABOVE FIELD CAPACITY                            */
/*
UTOP=URND(U);
BEGMR(2)=LDTLIM+UTOP*(UDTLIM-LDTLIM);
IF BEGMR(2) > 1.0 & SOILTYPE ¬= 2 THEN BEGMR(2)=1.0;
BEGMR(1)=BEGMR(2);
BEGMR(5)=LDBLIM+URND(U)*(UDBLIM-LDBLIM);
IF BEGMR(5) > 1.0 & SOILTYPE ¬=2 THEN BEGMR(5)=1.0;
BEGMR(6)=BEGMR(5);
BEGMR(3)=(2.0*BEGMR(2)+BEGMR(5))/3.0;
BEGMR(4)=(BEGMR(2)+2.0*BEGMR(5))/3.0;
DRYBEGSM=0.0;
DO J=1 TO 6;
  MOIS=BEGMR(J)*SMC(J);
  DRYBEGSM=DRYBEGSM+MOIS;
  SM(DRY,J)=MOIS;
```

```
END;                                                             */
/*                                                               */
/* ESTIMATE SPRING STARTING MOISTURE FOR IRRIGATED SOIL          */
/*
BEGMR(2)=LITLIM+UTOP*(UITLIM-LITLIM);
IF BEGMR(2) > 1.0 & SOILTYPE ¬= 2 THEN BEGMR(2)=1.0;
BEGMR(1)=BEGMR(2);
BEGMR(5)=LIBLIM+URND(U)*(UIBLIM-LIBLIM);
IF BEGMR(5) > 1.0 & SOILTYPE ¬= 2 THEN BEGMR(5)=1.0;
BEGMR(6)=BEGMR(5);
BEGMR(3)=(2.0*BEGMR(2)+BEGMR(5))/3.0;
BEGMR(4)=(BEGMR(2)+2.0*BEGMR(5))/3.0;
IRRBEGSM=0.0;
DO J=1 TO 6;
  MOIS=BEGMR(J)*SMC(J);
  IRRBEGSM=IRRBEGSM+MOIS;
  DO I=2 TO NDPOSN;
    SM(I,J)=MOIS;
  END;
END;
UTOP=URND(U);
PUT PAGE FILE(OYR) EDIT('SEED NUMBER=',INITSEED,'YEAR=',YEAR)
                      (X(15),A,F(6,0),X(10),A,F(3,0));
PUT SKIP(2) FILE(OYR) EDIT('CROP: ',NAME(CROP),METHOD(YLDMETH))
                       (X(4),A(6),A(7),X(10),A(17));

IF INDYRS = 1 THEN
 DO;
  PUT SKIP(3) FILE(OYR) EDIT('DRYLAND','IRRIGATED')(COL(35),
                          A(7),COL(54),A(9));
  PUT SKIP FILE(OYR) EDIT('DAY ','RAIN ',' PET ','PHENO-',
        '   SM ','  ET ','  YIELD ','  AREA ',' WATER ',
        '   SM ','  ET ','   YIELD')
         (X(1),12(A));
  PUT SKIP FILE(OYR)EDIT ('(mm) ','(mm) ','STAGE ','  (mm)',
         ' (mm)',' (kg/ha)','  (ha) ','(mm/ha)','  (mm)',' (mm)',
        ' (kg/ha)')
          (X(5),11(A));
  PUT SKIP(0) FILE(OYR) EDIT ((75)'_')(X(1),A);PUT SKIP FILE(OYR);
 END;
 END INITLIZ;                                                    */
 /*                                                              */
 /****************END OF INITLIZ**********************************/
 /*                                                              */
 /*                                                              */
 /****************************************************************/
 /*                                                              */
 /*                     WEATHER                                  */
 /*                                                              */
 /*  WEATHER GENERATES THE DAILY WEATHER FOR THE SIMULATION      */
 /*  PRECIPITATION EVENTS ARE ASSUMED TO FOLLOW A SIMPLE MARKOV  */
 /*  CHAIN; PRECIPITATION ON A WET DAY A CUBE ROOT NORMAL;       */
 /*  TMIN AND PET WERE BASED ON SIMPLE REGRESSION ANALYSIS ON    */
 /*  TMAX.                                                       */
 /*
 WEATHER:PROCEDURE;                                              */
 DCL (PRD,       /* SPECIFIC 10 DAY PERIOD                       */
      YSTWET)    /* YESTERDAYS WETNESS
        FIXED;                                                   */
 DCL (DD,        /* DAILY DEGDAYS                                */
      T,         /* TEMPORARY TEMPERATURE HOLDER
    CBRTRAIN)  /* CUBE ROOT OF DAILY RAINFALL                           */
    FLOAT;
PRD=FLOOR((DAY-99)/10)+1;
YSTWET=WET;
DD=0.0;                                                                 */
WET=0;  /* INITIALLY SET TO A DRY DAY                                   */
/*                                                                      */
/* SEE IF THE DAY IS WET OR DRY                                         */
/*                                                                      */
IF YSTWET = 0 THEN /* YESTERDAY WAS A DRY DAY
  DO;
   IF URND(U) <= PWD(PRD) THEN WET=1;
  END;                                                                  */
             ELSE /* YESTERDAY WAS A WET DAY
  DO;
   IF URND(U) <= PWW(PRD) THEN WET=1;
  END;                                                                  */
/*                                                                      */
/* DETERMINE HOW MUCH RAIN                                              */
/*
IF WET=1 THEN
  DO;
    CBRTRAIN=AVGRAIN(PRD)+GRND(G)*SDRAIN(PRD);                          */
    /*                                                                  */
    /* BY DEFINITION A WET DAY CAN'T HAVE < 0.25 mm                     */
    /*
    IF CBRTRAIN < 0.63 THEN CBRTRAIN=0.63;
    RAIN=CBRTRAIN**3;
  END;
        ELSE
  RAIN=0.0;                                                             */
/*                                                                      */
/* WHAT ARE THE DAY'S TEMPERATURES ?                                    */
/*
TMAX=AVGTMAX(PRD,WET)+GRND(G)*SDTMAX(PRD,WET);
TMIN=ATNTX(PRD,WET)+BTNTX(PRD,WET)*TMAX+GRND(G)*SDTNTX(PRD,WET);
IF TMIN > TMAX THEN       /* REVERSE TMIN AND TMAX */
  DO;
    T=TMIN;
    TMIN=TMAX;
    TMAX=T;
  END;                                                                  */
/*                                                                      */
/* ASSUME FROM JUNE 21 TO AUGUST 13 NO FROSTS CAN OCCUR                 */
/*
IF TMIN < -2.2 & (DAY > 172 & DAY < 225) THEN TMIN=-2.19;
TMEAN=(TMAX+TMIN)/2.0;                                                  */
/*                                                                      */
/* ESTIMATE PET FOR THE DAY                                             */
/*
PET=APETX(PRD,WET)+BPETX(PRD,WET)*TMAX+GRND(G)*SDPETX(PRD,WET);
IF PET < 0.01 THEN PET=0.01;                                            */
/*                                                                      */
/* CALCULATE AVERAGE DRY DAY PET                                        */
/*
DRYPET=APETX(PRD,0)+BPETX(PRD,0)*AVGTMAX(PRD,0);
TOTRAIN=TOTRAIN+RAIN;
TOTPET=TOTPET+PET;
CALL SUN;                                                               */
/*
```

```
/* ESTIMATE DEGREE DAYS AND DO SOME METEOROLICAL SUMS               */
/*                                                                  */
IF TMEAN > 5.0 THEN DD=TMEAN-5.0;
DEGDAYS=DEGDAYS+DD;
IF GROWING THEN
  DO;
    GSRAIN=GSRAIN+RAIN;
    GSDD=GSDD+DD;
  END;                                                              */
/*
/* + + + + + + + + + + + + + +SUN+ + + + + + + + + + + + + + + + + ++*/
                                                                    */
/*                                                                  */
/* SUN CALCULATES MANY VARIABLES WHICH DEPEND ON SUN                */
/*
SUN:PROCEDURE;                                                      */
DCL (DECLN,  /* SOLAR DECLENTION ANGLE (DEGREES)                    */
     SUNRISANG) /* ANGLE SUN MAKES AT SUNRISE OR SUNSET (RAD)       */
       FLOAT;
DCL CONVFAC     /*CONVERSION FACTOR ((cal/cm**2/d)/(W/m**2))        */
     FLOAT STATIC INITIAL(2.06366);
DECLN=23.45*SIND(0.9863*(DAY+284.0));
X=-TAND(LAT)*TAND(DECLN);
SUNRISANG=ATAN(SQRT(1.0-X*X)/X);
IF SUNRISANG<0.0 THEN SUNRISANG=SUNRISANG+3.14159;
XTERAD=430.674*((1.0+0.034*COSD(.9863*DAY))*
        (COSD(LAT)*COSD(DECLN)*SIN(SUNRISANG)+
        SUNRISANG*SIND(LAT)*SIND(DECLN)));
DAYLEN=7.63944*SUNRISANG;
TX=TMAX*9.0/5.0+32.0;
TN=TMIN*9.0/5.0+32.0;                                               */
/*                                                                  */
/* LE (LATENT EVAPORATION FORM BLACK BELLANI PLATE                  */
/* ATOMETER) CAN BE APPROXIMATED FROM PENMAN'S PET.                 */
/*
XT=XTERAD*CONVFAC;
LE=((PET-0.50)/0.763)*10.0;
END SUN;                                                            */
/*
/* + + + + + + + + + + END OF SUN + + + + + + + + + + + + + + + + + */
/*                                                                  */
END WEATHER;                                                        */
/*
/*****************END OF WEATHER***********************************/
/*                                                                  */
/*******************************************************************/
/*                                                                  */
/*                          URND                                    */
/*                                                                  */
/* URND GENERATES UNIFORMILY DISTRIBUTED RANDOM NUMBERS             */
/* WHICH VARY BETWEEN 0 AND 1                                       */
/*
URND:PROCEDURE(U);
     SEEDNUM=MOD((24298.0*SEEDNUM+99991.0),199017.0);
     RETURN(SEEDNUM/199017.0);
END URND;                                                           */
/*
/*****************END OF URND**************************************/
/*                                                                  */
/*******************************************************************/
                                                                    */
/*
```

```
                                                                      */
/*                         GRND                                       */
/*                                                                    */
/*  GRND GENERATES NORMALLY (GAUSSIAN) DISTIBUTED RANDOM              */
/*  NUMBERS WITH MEAN OF ZERO AND A STANDARD DEVIATION OF ONE.        */
/*                                                                    */
GRND:PROCEDURE(G);                                                    */
     DCL (U1,U2) FLOAT;  /* UNIFORM RANDOM NUMBERS
     U1=URND(U);
     IF U1=0.0 THEN U1=1.0E-6; /* SMALL CHANCE WILL TRY LOG(0)        */
     U2=URND(U);
     RETURN(SQRT(-2.2*LOG(U1))*COS(6.2832*U2));
END GRND;                                                             */
/*
/*****************END OF GRND*****************************************/
/*                                                                    */
/*                                                                    */
/*                                                                    */
/********************************************************************/
/*                                                                    */
/*                          PHENO                                     */
/*                                                                    */
/*  PHENO ESTIMATES THE SEEDING DATE OR DATE OF START OF               */
/* GROWTH AND THE HARVEST DATES.  PHENO ALSO ESTIMATES THE             */
/* GROWTH STAGE OF THE CROP.                                          */
/*
PHENO:PROCEDURE;
IF ¬EOSEAS THEN
  DO;
    IF CROP=WHEAT THEN CALL WHETBIO;
                  ELSE CALL FORBIO;
  END;                                                                */
 /*                                                                   */
 /*+ + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + */
 /*                                                                   */
 /*                     WHETBIO                                       */
 /*                                                                   */
 /* WHETBIO ESTIMATES THE STAGE IN THE DEVELOPMENT                    */
 /* OF A CROP OF WHEAT.  THIS MODEL WAS DEVELOPED FOR                 */
 /* MARQUIS WHEAT AND IS BASED ON PLOT TRIALS THROUGHOUT              */
 /* CANADA.  SOURCE: ROBERTSON (1968)                                 */
 /* A DUMMY VARIABLE IS USED TO SET THE PHOTOPERIOD                   */
 /* EFFECT TO 1 DURING P-E.                                           */
 /*
 WHETBIO:PROCEDURE;
 DCL REGCOEF(9,5) FLOAT STATIC INITIAL
 /*           P-E          E-J          J-H          H-S         S-R      */
 /* DM */ (   1,           0,           0,           0,          0,
 /* A0 */     0,           8.413,       10.93,       10.94,      24.38,
 /* A1 */     0,           1.005,       0.9256,      1.389,      -1.140,
 /* A2 */     0,           0,           -0.06025,    -0.08191,   0,
 /* B0 */     44.37,       23.64,       42.65,       42.18,      37.67,
 /* B1 */     0.01086,     -0.003512,   2.958E-4,    2.458E-4,   6.733E-5,
 /* B2 */     -2.230E-4,   5.026E-5,    0,           0,          0,
 /* B3 */     9.732E-3,    3.666E-4,    3.943E-4,    3.109E-5,   3.4442E-4,
 /* B4 */     -2.267E-4,   -4.282E-6,   0,           0,          0);
 DCL L FIXED; /*LIFESTAGE INDEX*/
 DCL (TX,             /*TMAX IN F */
      TN,             /*TMIN IN F */
      MXTERM,         /* TX-THRESHOLD TEMPERATURE (B0)                 */
      MNTERM,         /* TN-THRESHOLD TEMPERATURE (B0)                 */
      PHOTOTERM,      /* DAYLEN- THRESHOLD PHOTOPERIOD (A0)            */
    V1,             /* EFFECT OF PHOTOPERIOD ON PHENOLOGICAL   */
                    /* DEVELOPMENT                             */
    V2,             /* EFFECT OF TMAX ON DEVELOPMENT           */
    V3)             /* EFFECT OF TMIN ON DEVELOPMENT           */
   FLOAT;
IF (¬GROWING) THEN
  DO;
    IF BEGDAY>365 THEN CALL SEEDING;      /* CHECK FOR PLANTING */
                                          /*  CONDITIONS        */
  END;
              ELSE      /* ALREADY GROWING */
  DO;
    IF LIFESTAGE < 1 THEN LIFESTAGE=1;
    L=LIFESTAGE;
    IF TMIN<-2.5 THEN   /* CHECK FOR FROST */
      DO;
        /*                                                     */
        /* FROST BEFORE JOINTING DOES NOT KILL THE CROP        */
        /* BECAUSE THE GROWING POINT IS BELOW THE GROUND       */
        /* FROST DURING FINAL RIPENING CAUSES CROP DEATH AND   */
        /* FROST BETWEEN THESE TWO PERIODS CAUSES COMPLETE     */
        /* LOSS                                                */
        /*                                                     */
        IF PHENOSTAGE > 2.0 THEN
          DO;
            EOSEAS=TRUE;
            IF PHENOSTAGE < 4.50 THEN
              DO I=1 TO NDPOSN;
                YIELD(I)=0.0;
              END;
            GROWING=FALSE;
          END;
      END;
                  ELSE   /* NO FROST */
      DO;
        TX=TMAX*9./5.+32.;
        TN=TMIN*9./5.+32.;
        PHOTOTERM=DAYLEN-REGCOEF(2,L);
        /*                                                       */
        /* IF A TEMPERATURE IS BELOW THE THRESHOLD TEMPERATURE   */
        /* THEN THAT TEMPERATURE TERM IS SET TO ZERO             */
        /*                                                       */
        MXTERM=TX-REGCOEF(5,L);
        IF MXTERM < 0.0 THEN MXTERM=0.0;
        MNTERM=TN-REGCOEF(5,L);
        IF MNTERM < 0.0 THEN MNTERM=0.0;
        /*                                                       */
        /* V1, V2, &V3 ARE NOT ALLOWED TO BECOME NEGATIVE        */
        /* SINCE PHENOLOGICAL DEVELOPMENT IS NON-REVERSIBLE      */
        /*                                                       */
        V1=REGCOEF(1,L)+REGCOEF(3,L)*PHOTOTERM+
          REGCOEF(4,L)*PHOTOTERM**2;
        IF V1 < 0.0 THEN V1=0.0;
        V2=REGCOEF(6,L)*MXTERM+REGCOEF(7,L)*MXTERM**2;
        IF V2 < 0.0 THEN V2=0.0;
        V3=REGCOEF(8,L)*MNTERM+REGCOEF(9,L)*MNTERM**2;
        IF V3 < 0.0 THEN V3=0.0;
        PHENOSTAGE=PHENOSTAGE+V1*(V2+V3);
        /*                                                       */
        /* WHEN PHENOSTAGE REACHES 5 THEN CROP TRANSPIRATION     */
```

```
          /* HAS STOPPED AND CROP LIKELY SWATHED                       */
          /*                                                           */
          IF PHENOSTAGE > 5 THEN
            DO;
              EOSEAS=TRUE;
              ENDDAY=DAY;
              GROWING=FALSE;
            END;
                           ELSE
            DO;
              LIFESTAGE=CEIL(PHENOSTAGE);
              GSDAYS=DAY-BEGDAY+1;
            END;
          IF LIFESTAGE < 1 THEN LIFESTAGE=1;
  END;
/*                                                                   */
/*.. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .*/
/*                                                                   */
/*                      SEEDING                                      */
/*                                                                   */
/* SEEDING ESTIMATES THE DAY OF SEEDING OF THE WHEAT                 */
/* CROP.  SEEDING (AND START OF GROWTH) OCCURS AFTER 4 DAYS          */
/* OF LANDWORK PROVIDING A CERTAIN NUMBER OF DEGREE DAYS HAS         */
/* BEEN ACCUMULATED (INDICATING THE SOIL IS WARM ENOUGH).            */
/* LANDWORK IS BASED ON SOIL TRACTABILTIY OF IRRIGATED SOIL          */
/*                                                                   */
SEEDING:PROCEDURE;
DCL MINDD FLOAT                  /* MINIMUM DEGDAYS TO WARM UP SOIL */
          STATIC INITIAL(70),
    LANDWORK BIT(1);                /* SOIL TRACTABLE FLAG           */
LANDWORK=FALSE;
/*                                                                   */
/* THE FOLLOWING SECTION DETERMINES THE SOIL TRACTABILITY            */
/* STATUS TO SEE IF THE DAY IS A POSSIBLE WORKDAY                    */
/* THE TRACTABILITY CRITERIA ARE FROM DYER ET AL. (1978)             */
/* LIGHT SOIL: AM(1,2,3)=(0.95,0.95,0.98)                            */
/* MEDIUM TO HEAVY SOIL: AM(1,2,3)=(0.90,0.90,0.90)                  */
/*                                                                   */
DO J=1 TO 3;
  IF SM(2,J)/SMC(J) < TRACAM(J) THEN LANDWORK=TRUE;
                                 ELSE LANDWORK=FALSE;
END;
IF LANDWORK & DEGDAYS > MINDD THEN SEEDDAYS=SEEDDAYS+1;
   IF SEEDDAYS > 3 THEN /* SEEDING IS COMPLETE */
     DO;
       BEGDAY=DAY;
       LIFESTAGE=1;
       PHENOSTAGE=0;
       GROWING=TRUE;
       GSDAYS=1;
     END;
END SEEDING;
/*                                                                   */
/* . . . . . . . . . . END OF SEEDING . .. . . . . . . . . . . . . . */
/*                                                                   */
END WHETBIO;
/*                                                                   */
/*+ + + + + + + + + + + +END OF WHETBIO+ + + + + + + + + + + + + + ++*/
/*                                                                   */
/*+ + + + + + + + + + + + + + FORBIO + + + + + + + + + + + + + + + ++*/
```

```
/*                                                                    */
/* FORBIO ESTIMATES THE STAGE OF GROWTH OF FORAGE                     */
/* THE METHOD IS FROM SELIRIO AND BROWN'S SIMFOY (1979)               */
/* THE FORAGE IS HARVESTED WHEN 500 DEGREE DAYS ARE ACCUMULATED       */
/* & IT IS ASSUMED FULL GROUND COVER IS ATTAINED AT 250 DEGDAYS       */
/*                                                                    */
FORBIO:PROCEDURE;
DCL PREDD            /* DEGDAYS BEFORE CROP BEGINS GROWING            */
      FLOAT STATIC;
DCL ALFDD            /* MINIMUM NUMBER OF DEGDAYS BEFORE CROP         */
                     /* CAN BEGIN GROWING                             */
     FLOAT STATIC INITIAL (40.0);
DCL CASE(5) LABEL;
IF (¬GROWING) THEN
   DO;
     /*                                                               */
     /* GROWTH CAN START ONLY WHEN ALFDD HAS BEEN ACHIEVED AND        */
     /* NO FROST                                                      */
     /*                                                               */
     IF DEGDAYS > ALFDD & TMIN > -2.2 THEN
       DO;
         GROWING=TRUE;
         BEGDAY=DAY;
         GADAYS(1)=1;
         PREDD=DEGDAYS;
       END;
   END;
          ELSE                        /* CROP IS GROWING              */
   DO;
     /*                                                               */
     /* A FROST BELOW -2.2 IS CONSIDERED A DAMAGING FROST --           */
     /* IN THE LATE SUMMER AND EARLY FALL IT INDUCES DORMANCY,        */
     /* IN THE SPRING NO GROWTH OCCURS ON THAT DAY                    */
     /*                                                               */
     IF TMIN < -2.2 THEN
       DO;
         /*                                                           */
         /* ADJUST YIELDS IF FROST DURING FIRST GROWTH                */
         /*                                                           */
         IF PHENOSTAGE < 1.0 THEN  /* SPRING OR EARLY SUMMER?         */
           DO;
             TMEAN=-5.0;/* LOWER TMEAN SO NO GROWTH                   */
             GOTO ENDFOR;
           END;
                  ELSE /* FROST CAUSES DORMANCY                       */
           DO;
             GROWING=FALSE;
             EOSEAS=TRUE;
             ENDDAY=DAY;
           END;
       END;
              ELSE        /* NO FROST                                 */
       DO;
         PHENOSTAGE=(DEGDAYS-PREDD)/500;
         LIFESTAGE=CEIL(PHENOSTAGE*2.0);
         D=PHENOSTAGE-FLOOR(PHENOSTAGE);
         IF D > 1.0 THEN D=1.0;
         IF LIFESTAGE < 1 THEN LIFESTAGE=1;
         IF LIFESTAGE > 5 THEN LIFESTAGE=5;
         GROWTH=FLOOR((LIFESTAGE+1)/2);
         IF GROWTH < 1 THEN GROWTH=1;
         GSDAYS=DAY-BEGDAY+1;
         GOTO CASE(LIFESTAGE);
           CASE(1):;
           CASE(2): GADAYS(1)=DAY-BEGDAY+1;
                    GOTO ENDFOR;
           CASE(3): IF FCDAY > 365 THEN FCDAY=DAY; /*FIRST CUT*/
           CASE(4): GADAYS(2)=DAY-FCDAY+1;
                    GOTO ENDFOR;
           CASE(5): IF (SCDAY>365)THEN SCDAY=DAY;/* SECOND CUT */
                    GADAYS(3)=DAY-SCDAY+1;
                    GOTO ENDFOR;
       END;
ENDFOR:END FORBIO;
/*                                                              */
/*+ + + + + + + +END OF FORBIO + + + + + + + + + + + + + + + + ++*/
/*                                                              */
END PHENO;
/*                                                              */
/****************END OF PHENO************************************/
/*                                                              */
/***********************VSMB*************************************/
/*                                                              */
/*                          VSMB                                */
/*                                                              */
/* PROCEDURE VSMB IS A VERSION OF BAIER AND ROBERTSON'S         */
/* VERSATILE SOIL MOISTURE BUDGET.  IN VSMB THE SOIL IS DIVIDED */
/* INTO SIX ZONES REPRESENTING 5.0, 7.5, 12.5, 25.0, 25.0,      */
/* & 25.0% RESPECTIVELY OF TOTAL AM IN THE ENTIRE ROOTING ZONE  */
/* VSMB ALSO CALCULATES THE ET.  INFILTRATION OCCURS AT THE     */
/* END OF THE DAY.                                              */
/*                                                              */
VSMB:PROCEDURE;
DCL (RUNOFF,            /* DAILY RUNOFF FROM LAND AREA (mm/ha)   */
     PE,                /* PET LESS TODAY'S INTERCEPTION (mm/d)  */
     DEEPPERC)          /* DAILY DEEP PERCOLATION BELOW THE ROOT */
                        /* ZONE (mm/ha)                          */
       FLOAT;
                        /*                                       */
DCL (RR,                /* RAINFALL+IRRIGATION (mm)              */
                        /* RAINFALL AND IRRIGATION ARE ASSUMED TO */
                        /* OCCUR AT THE END OF THE DAY AFTER ALL */
                        /* OF THE ET HAS ALREADY TAKEN PLACE     */
    RIN,                /* RAINFALL IN INCHES                    */
    LNRIN,              /* LN(RIN)                               */
    INTCEPT,            /* FOLIAR INTERCEPTION (mm)              */
    IN(6),              /* INFILTRATION INTO EACH SOIL ZONE (mm/d)*/
    DEFCIT(6),          /* (FC-SM) FC=FIELD CAPACITY             */
    AE(6),              /* ET FOR EACH SOIL ZONE                 */
    Z(6),               /* Z=(ET/PET)/AM FOR EACH ZONE           */
    K(6))               /* CROP MOISTURE EXTRACTION COEFFICIENTS */
       FLOAT;
DCL (TOTIN,             /* TOTAL INFILTRATION INTO TNE SOIL      */
                        /* PROFILE (mm/d)                        */
     XS)                /* EXCESS WATER WHICH CAN NOT PERCOLATE  */
                        /* BELOW THE ROOT ZONE BECAUSE OF RE-    */
                        /* STRICTED PERMEABILITY OF BOTTM LAYER  */
       FLOAT;
DCL (J,I,               /* COUNTERS                              */
     P)                 /* ALIAS POSN                            */
    FIXED;
DCL (SRFINF,            /* INFILTRATION INTO TOP SOIL ZONE  (mm)  */
     RAININF)           /* INFILTRATION FROM RAIN IN INCHES       */
    FLOAT;
P=POSN;
DO J=1 TO 6;
  AM(P,J)=SM(P,J)/SMC(J);
  IF AM(P,J)>1.0 THEN AM(P,J)=1.0;
END;
CALL KCOEFF;        /* CALCULATE THE K COEFFICIENT FOR EACH ZONE */
CALL ZTABLE;        /* CALCULATE THE Z COEFFICIENT FOR EACH ZONE */
RR=RAIN+IRR(P);
/*                                                               */
/* THE NEXT BLOCK ESTIMATES FOLIAR INTERCEPTION                   */
/* INTERCEPTION FROM DE JONG AND SHAYKEWICH (1981)               */
/* NO INTERCEPTION IF CROP COVER IS SPARSE                       */
/*                                                               */
INTCEPT=0.0;
PE=PET;
IF CROP = ALFALFA & D < 0.2 THEN GOTO NOINT;
IF CROP = WHEAT & (PHENOSTAGE < 2.0 | PHENOSTAGE > 5.0) THEN
  GOTO NOINT;
IF RR > 1.7 THEN INTCEPT=1.0+RR/(0.5*(RR+15.));
           ELSE INTCEPT=RR;
/*                                                               */
/* SUBTRACT INTERCEPTION FROM THIS DAY'S RAIN OR IRRIGATION       */
/* FROM THIS DAY'S PET                                           */
/*                                                               */
IF INTCEPT >= PET THEN
  DO;
    PE=0.01;
    INTCEPT=PET;
  END;
                ELSE PE=PET-INTCEPT;
NOINT:;
/*                                                               */
/* THE NEXT BLOCK ALLOCATES ET FROM EACH SOIL ZONE               */
/*                                                               */
ET(P)=0.0;
EVAPT: DO J=1 TO 6;
          AE(J)=K(J)*AM(P,J)*Z(J)*PE;
          IF AE(J) > SM(P,J) THEN AE(J)=SM(P,J);
          ET(P)=ET(P)+AE(J);
          SM(P,J)=SM(P,J)-AE(J);
       END EVAPT;
ET(P)=ET(P)+INTCEPT;  /* ADD INTCEPT BACK TO ET                  */
TOTET(P)=TOTET(P)+ET(P);
IF GROWING THEN GSET(P)=GSET(P)+ET(P);
/*                                                               */
/* THE NEXT SECTION ESTIMATES INFILTRATION FROM RAINFALL         */
/* ALL RAINFALL < 1.0 INCHES INFILTRATES.  ONLY RAINFALL         */
/* CAUSES RUNOFF SINCE IRRIGATION SYSTEM IS DESIGNED TO          */
/* MINIMIZE RUNOFF                                               */
/*                                                               */
RIN=RAIN/25.4;
IF RIN > 1.0 THEN
  DO;
    LNRIN=LOG(RIN);
    RAININF=0.9177+1.811*LNRIN-.97*AM(P,1)*LNRIN;
    IF RAININF > RIN THEN RAININF=RIN;
  END;
                ELSE RAININF=RIN;             /* < 1 INCH OF RAIN    */
RUNOFF=(RIN-RAININF)*25.4;
TOTRUNOFF(P)=TOTRUNOFF(P)+RUNOFF;
SRFINF=RR-RUNOFF-INTCEPT;
/*                                                                     */
/* THE NEXT BLOCK DETERMINES INFILTRATION INTO LOWER ZONES             */
/*                                                                     */
IF SRFINF > 0.0 THEN
  DO;
     DO J=1 TO 6;
       DEFCIT(J)=SMC(J)-SM(P,J);
       IF DEFCIT(J) < 0.0 THEN DEFCIT(J)=0.0;
     END;
     TOTIN=0.0;
     DO J=1 TO 6 WHILE (TOTIN < SRFINF );
        IF (AM(P,J)<0.9) THEN /* MAKE PERCOLATION ADJUSTMENT           */
                               /* TO ALLOW PERCOLATION BEFORE           */
                               /* FIELD CAPACITY IS REACHED             */
          DO;
             IN(J)=(1-AM(P,J)*PERCOEF(J))*(SRFINF-TOTIN);
             IF (IN(J)>DEFCIT(J))THEN IN(J)=DEFCIT(J);
          END;
                           ELSE   /* NO PERCOLATION ADJUSTMENT          */
          DO;
             IF (DEFCIT(J)<(SRFINF-TOTIN)) THEN
               IN(J)=DEFCIT(J);
                                               ELSE
               IN(J)=SRFINF-TOTIN;
          END;
          SM(P,J)=SM(P,J)+IN(J);
          TOTIN=TOTIN+IN(J);
     END;
     /*                                                                 */
     /* THIS NEXT BLOCK DETERMINES DEEP PERCOLATION                     */
     /* IF DEEP PERCOLATION  > THE PERMEABILITY OF THE                  */
     /* UNDERLYING LAYER THEN THE SOIL CAN BECOME SATURATED             */
     /* (I.E. > FC). THE SOIL BECOMES SATURATED FROM THE BOTTOM         */
     /* UP I.E. A PERCHED WATER TABLE. EXCESS MOISTURE WHICH            */
     /* THE SOIL CAN NOT HOD BECOMES SURFACE RUNOFF.                    */
     /*                                                                 */
     XS=0.0;
     DEEPPERC=SRFINF-TOTIN;
     IF DEEPPERC > BOTPERM THEN
       DO;
          XS=DEEPPERC-BOTPERM;
          DEEPPERC=BOTPERM;
          DO I=6 TO 1 BY -1 WHILE (XS > 0.0);
            SM(P,I)=SM(P,I)+XS;
            IF SM(P,I) > SMSAT(I) THEN
               DO;
                 XS=SM(P,I)-SMSAT(I);
                 SM(P,I)=SMSAT(I);
               END;
                                     ELSE
               XS=0.0;
          END;
       END;
       TOTRUNOFF(P)=TOTRUNOFF(P)+XS;
       TOTDEEPERC(P)=TOTDEEPERC(P)+DEEPPERC;
```

```
 END;
/*                                                                    */
/** + + + + + + + + + + + + +KCOEFF + + + + + + + + + + + + + + + + + */
/*                                                                    */
/*                            KCOEFF                                  */
/*                                                                    */
/* KCOEFF ESTIMATES THE CROP (I.E. K ) COEFFICIENTS                   */
/* THE K COEFFICIENTS INDICATE THE PLANT ROOTING                      */
/* CHARACTERISTICS                                                    */
/*                                                                    */
KCOEFF:PROCEDURE;
      DCL L FIXED,     /* LIFESTAGE FOR K                             */
          (SUM,        /* SUM OF UPPER KCOEFF                         */
           TOPAM)      /* AM OF UPPER THREE ZONES                     */
             FLOAT;
        /*                                                            */
        /* THESE CROP COEFFICIENTS ARE FROM BAIER'S VSMB(1979)        */
        /* AND SCOTT(1975)                                            */
        /*                                                            */
      DCL CROPCOEFF(6,5,2) FLOAT STATIC INITIAL
/*      P-E|SG-FC    E-J|FC-1C    J-H|1C-FC    H-S|FC-2C    S-R|2C->*/
/*ZONE  W      A     W      A     W      A     W      A     W      A */
/*1*/( .43,  .50,  .47,  .50,  .45,  .50,  .40,  .50,  .40,  .45,
/*2*/  .15,  .20,  .23,  .25,  .28,  .22,  .31,  .25,  .29,  .25,
/*3*/  .13,  .15,  .16,  .23,  .17,  .18,  .22,  .25,  .20,  .20,
/*4*/  .10,  .12,  .14,  .22,  .13,  .15,  .18,  .20,  .15,  .20,
/*5*/  .03,  .08,  .03,  .15,  .12,  .15,  .15,  .18,  .07,  .20,
/*6*/  .01,  .05,  .02,  .10,  .05,  .10,  .09,  .12,  .04,  .15);
/*                                                                    */
/*SUM=0.85  1.10  1.05  1.45  1.20  1.30  1.35  1.50  1.15  1.45*/
/*                                                                    */
        DCL (M,J)              /* COUNTERS                            */
            FIXED;
        DCL KBARE(6)           /* K COEFFICIENTS WHEN THERE IS NO     */
                               /* GROWTH                              */
           FLOAT STATIC INITIAL(0.6,0.15,0.05,0.0,0.0,0.0);
        IF (¬GROWING) THEN
           DO J=1 TO 6;
             K(J)=KBARE(J);
           END;
                  ELSE    /*GROWING */
           DO;
             IF LIFESTAGE < 1 THEN LIFESTAGE=1;
             L=LIFESTAGE;
             DO J=1 TO 6;
               K(J)=CROPCOEFF(J,L,CROP);
             END;
             /*                                                       */
             /* IF THE AVERAGE AM OF THE UPPER 25% OF THE             */
             /* SOIL IS < 0.25 THEN ADJUST LOWER K'S TO ALLOW         */
             /* MORE MOISTURE EXTRACTION FROM LOWER ZONES             */
             /*                                                       */
             TOPAM=0.0;
             DO II=1 TO 3;
               TOPAM=TOPAM+SM(P,II)/SMC(II);
             END;
             IF TOPAM < 0.75 THEN
               DO J=3 TO 6;
                 SUM=0.0;
                 DO JJ=1 TO J-1;
                 SUM=SUM+CROPCOEFF(JJ,L,CROP)*(1.0-AM(P,JJ));
               END;
               K(J)=K(J)+K(J)*SUM;
             END;
         END;
END KCOEFF;
/*                                                                   */
/*+ + + + +END OF KCOEFF+ + + + + + + + + + + + + + + + + + + + + + + */
/*                                                                   */
/*+ + + + + + + + ZTABLE+ + + + + + + + + + + + + + + + + + + + + + + */
/*                                                                   */
/*                 ZTABLE                                            */
/*                                                                   */
/* ZTABLE ESTIMATES THE Z (I.E. ET/PET/AM) FOR EACH                  */
/* SOIL ZONE.  ET/PET CANNOT BE LESS THAN 0.00 OR                    */
/* ABOVE 1.0                                                         */
/*
ZTABLE:PROCEDURE;
DCL FINISHED BIT(1);
DCL MR FLOAT;     /* AM FOR A SOIL ZONE                              */
/*                                                                   */
/* IF THE SOIL IS SATURATED THAN NO ET TAKES PLACE IE Z=0            */
/* UNLESS SOIL ZONE ABOVE 0.95 OF SATURATION. THIS MODIFICATION      */
/* IS FROM DE JONG AND SHAYKEWICH (1981)                             */
/*
FINISHED=FALSE;
DO J=1 TO 6 WHILE (¬FINISHED);
  /*                                                                 */
  /* BELOW THE SURFACE LAYER CHECK IF THE ZONES ARE ALMOST           */
  /* SATURATED.  ROOTS ARE DEAD BELOW A SATURATED ZONE               */
  /*                                                                 */
  IF J>2 THEN
    DO;
      IF SM(P,J-1)>(.95*SMSAT(J-1)) THEN
        BEGIN;
          DO I=J TO 6;
            Z(I)=0.05;
          END;
          FINISHED=TRUE;
        END;
    END;
  IF ¬FINISHED THEN
    DO;
      /*                                                             */
      /* THIS Z FUNCTION IS FROM EAGLEMAN (1971)                     */
      /*                                                             */
      MR=AM(P,J);
      IF MR <= 0.0 THEN Z(J)=0.0;
                   ELSE
        DO;
          Z(J)=((-0.050+0.732/PET)/MR+(4.97-0.661*PET)+
                (-8.57+1.56*PET)*MR+(4.35-0.880*PET)*MR*MR);
          IF Z(J) < 0.0 THEN Z(J)=0.0;
          IF Z(J)*MR > 1.00 THEN Z(J)=1.00/MR;
        END;
    END;
END;
END ZTABLE;
/*                                                                   */
/* + + + + + + + END OF ZTABLE + + + + + + + + + + + + + + + + + + + +*/
/*                                                              */
END VSMB;
/*                                                              */
/*************END OF VSMB****************************************/
/*                                                              */
/******************THEOYLD***************************************/
/*                                                              */
/*                 THEOYLD                                      */
/*                                                              */
/* PROCEDURE THEOYLD ESTIMATES OF THE YIELDS OF                 */
/* THE CROPS WITH MOISTURE NOT LIMITING.                        */
/*                                                              */
THEOYLD:PROCEDURE;
GSPET=GSPET+PET;
IF CROP=WHEAT THEN
  CALL T_WAGEN;
              ELSE           /* ALFALFA */
  IF YLDMETH=1 THEN CALL T_SMFOY;
               ELSE CALL T_FEDDS;
/*                                                              */
/*                                                              */
/* + + + + + + + + + + +T_WAGEN + + + + + + + + + + + + + + + + */
/*                                                              */
/* T_WAGEN USES THE WAGENINGEN METHOD TO ESTIMATE WHEAT YIELDS  */
/* IN kg/ha GRAIN @ 14.5% m.c.                                  */
/*                                                              */
T_WAGEN:PROCEDURE;
DCL (TEMPFAC,     /* FACTOR WHICH TAKES INTO ACCOUNT THE EFFECT */
                  /* OF TEMPERTURE ON CROP GROWTH               */
     COVERFAC,    /* FACTOR WHICH TAKES INTO ACCOUNT THE EFFECT */
                  /* OF SOIL COVER (I.E. LAI) ON CROP GROWTH    */
     LAI,         /* LEAF AREA INDEX                            */
     GS,          /* LENGTH CROP HAS BEEN GROWING NORMALIZED    */
                  /* TO 130 DAYS TOTAL GROWING SEASON.  GS IS   */
                  /* ONLY ESTIMATED AFTER CROP HAS EMERGED      */
     F,           /* PROPORTION OF DAY SKY IS OVERCAST          */
     PO,          /*PHOTOSYNTHETIC FLUX ON OVERCAST DAY (kg/ha/d)*/
     PC,          /*PHOTOSYNTHETIC FLUX ON A CLEAR DAY (kg/ha/d) */
     PST)         /* ACTUAL PHOTOSYNTHETIC FLUX (kg/ha/d)       */
        FLOAT;
DCL DMCONV        /* CONVERTS DRY MATTER TO 14.5% m.c.          */
     FLOAT STATIC INITIAL (1.17);
DCL HRVNDX        /* % WHICH IS GROSS GROWTH WHICH IS GRAIN     */
     FLOAT STATIC INITIAL(0.30);
CALL PHOTO(PO,PC,F);
TEMPFAC=-0.514+0,121*TMEAN-0.00341*TMEAN**2;
IF TEMPFAC < 0.0 THEN TEMPFAC=0.0;
PST=F*PO+(1.0-F)*PC;
/*                                                              */
/* NEXT SECTION ESTIMATES LAI AND COVERFAC.                     */
/*                                                              */
IF PHENOSTAGE < 1.0 THEN
  GS=GSDAYS;
                      ELSE
     GS=130.0*PHENOSTAGE/5.0;
 IF GS <= 42 THEN
    LAI=2.77E-05*GS**3.113;
                 ELSE
    LAI=6.691-0.9106*GS+0.0398*GS**2-6.529E-04*GS**3+
        4.693E-06*GS**4-1.257E-08*GS**5;
```

```
IF LAI < 5.0 THEN
   COVERFAC=LAI/5.0;
             ELSE
   COVERFAC=1.0;
YPOT=1.17*PST*COVERFAC*TEMPFAC*DMCONV*HRVNDX*MNGFAC/PET;
POTYIELD=POTYIELD+YPOT*PET;
END T_WAGEN;
/*                                                               */
/* + + + + + + + + + + END OF T_WAGEN + + + + + + + + + + + + + */
/*                                                               */
/*+ + + + + + + + + + + + + + + + + + + + + + + + + + + + + + + */
/*                                                               */
/*                    T_SMFOY                                    */
/*                                                               */
/* T_SMFOY ESTIMATES THE FORAGE YIELD ACCORDING TO THE           */
/* METHOD OF SELIRIO AND BROWN (1979).  YIELD IS @ 15% m.c.      */
/*                                                               */
T_SMFOY:PROCEDURE;
DCL  PRVPAFY(3)        /* PREVIOUS DAY'S POTENTIAL YIELD FOR EACH  */
                       /* OF THE THREE GROWTH STAGES (kg/ha)       */
      FLOAT;
DCL  YLDLEV(3)         /* YIELD CEILING FOR THE 1ST, 2ND & 3RD     */
                       /* GROWTHS (kg/ha)                          */
      FLOAT STATIC INITIAL
         (12000.0,7000.0,5000.0); /* YIELD CEILING OF 18t/ha IN */
                                  /* 2 CUTS                      */
DCL DMCONV             /* CONVERTS DRY MATTER TO 15% m.c.          */
      FLOAT STATIC INITIAL (1.18);
PRVPAFY(GROWTH)=POTAFYLDS(GROWTH);
POTAFYLDS(GROWTH)=DMCONV*YLDLEV(GROWTH)/(1.0+EXP(5.3-6.7*SQRT(D)));
YPOT=POTAFYLDS(GROWTH)-PRVPAFY(GROWTH);
POTYIELD=POTYIELD+YPOT;
END T_SMFOY;
/*                                                               */
/* + + + + + + + + +END OF T_SMFOY+ + + + + + + + + + + + + + + */
/*                                                               */
/* + + + + + + + + + + +T_FEDDS + + + + + + + + + + + + + + + + */
/*                                                               */
/* T_FEDDS -- CROP MODEL DEVELOPED BY FEDDES, KOWALIK,           */
/* AND ZARADANY (1979) AS PRESENTED AND MODIFIED BY              */
/* SLABBERS ET AL. (1979).  THE FEDDES MODEL IS BASED ON         */
/* THE WAGENINGEN METHOD.                                        */
/* THIS MODEL IS USED TO ESTIMATE ALFALFA YIELDS @ 15% MOISTURE */
/* (kg/ha)                                                       */
/*                                                               */
T_FEDDS:PROCEDURE;
DCL (F,           /* PROPORTION OF DAY SKY IS OVERCAST             */
    PO,           /* PHOTOSYNTHETIC FLUX ON OVERCAST DAY (kg/ha/d) */
    PC,           /* PHOTOSYNTHETIC FLUX ON A CLEAR DAY (kg/ha/d)  */
    PST,          /* ACTUAL PHOTOSYNTHETIC FLUX (kg/ha/d)          */
    TEMPFAC,      /* TEMPERTURE EFFECT ON CROP GROWTH              */
    COVERFAC)     /* SOIL COVER (LAI) EFFECT ON PRODUCTION         */
       FLOAT;
DCL PHOTOEFF      /* PHOTOSYNTHETIC EFFICIENCY                     */
       FLOAT STATIC INITIAL(0.6);
DCL DMCONV        /* CONVERTS DRY MATTER TO 15% m.c.               */
       FLOAT STATIC INITIAL(1.18);
CALL PHOTO (PO,PC,F);
PST=F*PO+(1.0-F)*PC;
CALL EPSI(TEMPFAC);
CALL SIGM(COVERFAC);
YPOT=PHOTOEFF*DMCONV*TEMPFAC*COVERFAC*PST*MNGFAC/PET;
POTAFYLDS(GROWTH)=POTAFYLDS(GROWTH)+YPOT;                        */
/*                                                               */
/* POTENTIAL YIELD IS WITH MAXIMUM TOPPOR I.E. 0.935             */
/*
POTYIELD=POTYIELD+YPOT*0.935*PET;                                */
/*                                                               */
/* . . . . . . . . . SIGM . . . . . . . . . . . . . . . . . . . .*/
/*                                                               */
/* SIGM RETURNS THE COVER FACTOR (SIGMA) WHICH TAKES             */
/* INTO ACCOUNT THE EFFECT OF LEAF AREA ON CROP PRODUCTION       */
/* THIS FUNCTION IS QUITE ARBRITRARY.  COVERFAC ONLY REACHES     */
/* ONE DURING THE LATTER STAGES OF THE FIRST GROWTH              */
/*
SIGM:PROCEDURE(COVERFAC);
DCL COVERFAC
     FLOAT;
COVERFAC=EXP(1.40*D)-1.0;
IF COVERFAC > 1.0 THEN COVERFAC=1.0;
IF LIFESTAGE > 2 THEN COVERFAC=COVERFAC*0.9;
END SIGM;                                                        */
/*                                                              .*/
/* . . . . . . . END OF SIGM . . . . . . . . . . . . . . . . . . */
/*                                                              .*/
/* . . . . . . . . . EPSI . . . . . . . . . . . . . . . . . . .  */
/*                                                               */
/*  EPSI ESTIMATES THE TEMPERATURE FACTOR WHICH TAKES INTO       */
/* TEMPERATURE EFFECTS ON CROP PRODUCTION. THE TEMPERATURE       */
/* EFFECTS ARE DIFFERENT IN THE SPRING THAN IN THE SUMMER & FALL*/
/*                                                               */
EPSI:PROCEDURE(TEMPFAC);
IF PHENOSTAGE <= 2 THEN    /*SPRING*/
   TEMPFAC=-0.43610+0.130775*TMEAN-0.0028296*TMEAN**2;
                    ELSE   /*SUMMER-FALL*/
   TEMPFAC=-1.28706+0.180495*TMEAN-0.003549*TMEAN**2;
IF TEMPFAC < 0.0 THEN TEMPFAC=0.0;
IF TEMPFAC > 1.0 THEN TEMPFAC=1.0;
END EPSI;                                                        */
/*                                                              .*/
/* . . . . . . . . . END OF EPSI . . . . . . . . . . . . . . .   */
/*
END T_FEDDS;                                                     */
/*                                                               */
/* + + + + + + + END OF T_FEDDS + + + + + + + + + + + + + + + + + */
/*                                                               */
/*                                                               */
/*+ + + + + + + + +PHOTO + + + + + + + + + + + + + + + + + + + + +*/
/*                                                               */
/* PROCEDURE PHOTO CALCULATES THE PHOTOSYNTETIC                  */
/* FLUXES ON CLEAR AND OVERCAST DAYS.                            */
/* PHOTO ALSO ESTIMATES THE FRACTION OF THE DAY THE              */
/* SKY IS OVERCAST FROM BAIER AND ROBERTSON'S SIMPLE             */
/* ESTIMATION OF PET                                             */
/*
PHOTO:PROCEDURE(PO,PC,F);
DCL (PO,     /* PHOTOSYNTHETIC FLUX ON AN OVERCAST DAY (kg/ha/d)*/
     PC,     /* PHOTOSYNTHETIC FLUX ON A CLEAR DAY (kg/ha/d)    */
     F)      /* PROPORTION OF THE DAY THE SKY IS OVERCAST       */
        FLOAT;
```

```
/*                                                               */
/* PD & PC APPROXIMATIONS ARE GOOD BETWEEN 40 AND 60 DEG N       */
/*                                                               */
PD=18.81+0.143556*XTERAD*(3.0+SIND(LAT));
PC=80.326+0.250694*XTERAD*(3.0+SIND(LAT));
/*                                                               */
/* THE NEXT SECTION ESTIMATES F                                  */
/*                                                               */
/* THE PROPORTION OF THE DAY THE SKY IS OVERCAST IS              */
/* ESTIMATED FROM BAIER AND ROBERTSON'S (1966) SIMPLE            */
/* METHOD OF ESTIMATING LE FROM MAXIMUM AND MINIMUM              */
/* DAILY TEMPERATURES, EXTRATERRESTIAL RADIATION AND             */
/* ACTUAL SOLAR RADIATION                                        */
/*                                                               */
F=((-LE-55.67+0.687*TX+0.284*(TX-TN)+0.0263*XT)/XT+
   0.0594)/0.0422;
IF F > 1.0 THEN F=1.0;
IF F < 0.0 THEN F=0.0;
END PHOTO;
/*                                                               */
/* + + + + + + + + + END OF PHOTO + + + + + + + + + + + + + + + + */
/*                                                               */
END THEOYLD;
/*                                                               */
/******************END OF THEOYLD*******************************/
/*                                                               */
/******************YLDEST***************************************/
/*                                                               */
/*                  YLDEST                                       */
/*                                                               */
/* PROCEDURE YLDEST ESTIMATES OF THE YIELDS OF                   */
/* THE CROPS WITH MOISTURE LIMITATIONS                           */
/*                                                               */
YLDEST:PROCEDURE;
 DCL    YACT            /* ACTUAL DAILY GROWTH (kg/ha)           */
          FLOAT;
IF CROP = WHEAT THEN
   CALL WAGEN;
                ELSE                    /* ALFALFA */
  IF YLDMETH=1 THEN CALL SIMFOY;
               ELSE CALL FEDDES;
/*                                                               */
/* + + + + + + + + + + + WAGEN + + + + + + + + + + + + + + + + +*/
/*                                                               */
/* WAGEN USES THE WAGENINGEN METHOD TO ESTIMATE WHEAT YIELDS     */
/*                                                               */
WAGEN:PROCEDURE;
/*                                                               */
/* NO EXTRA SENSITIVITY TO MOISTURE STRESS DURING VEGETATIVE     */
/* GROWTH OR FINAL RIPENING                                      */
/*                                                               */
IF PHENOSTAGE < 3.0 | PHENOSTAGE > 4.5 THEN
  AWMSF(POSN)=AWMSF(POSN)+1.0;
                                          ELSE
  IF PHENOSTAGE < 3.5 THEN /* FLOWERING */
    AWMSF(POSN)=AWMSF(POSN)+1.0-1.50*(1.0-ET(POSN)/PET);
                       ELSE /* YIELD FORMATION */
    AWMSF(POSN)=AWMSF(POSN)+1.0-0.50*(1.0-ET(POSN)/PET);
WMSF(POSN)=AWMSF(POSN)/GSDAYS;
/*                                                               */
/* WMSF > 1.0 OR < 0.0 HAS NO PHYSICAL INTERPRETATION               */
/*                                                                  */
IF WMSF(POSN) > 1.0 THEN WMSF(POSN)=1.0;
                    ELSE
  IF WMSF(POSN) < 0.0 THEN WMSF(POSN)=0.0;
YACT=YPOT*ET(POSN);
YIELD(POSN)=YIELD(POSN)+YACT;
END WAGEN;
/*                                                                  */
/* + + + + + + +END OF WAGEN + + + + + + + + + + + + + + + + + + + +*/
/*                                                                  */
/*+ + + + + + + + + +SIMFOY + + + + + + + + + + + + + + + + + + + + */
/*                                                                  */
/*                        SIMFOY                                    */
/*                                                                  */
/* SIMFOY ESTIMATES THE FORAGE YIELD ACCORDING TO THE               */
/* METHOD OF SELIRIO AND BROWN (1979)                               */
/*                                                                  */
SIMFOY:PROCEDURE;
DCL CRITAM       /* AM BELOW WHICH CROP YIELD IS REDUCED -> 80% */
     FLOAT STATIC INITIAL(0.8);
DCL AMTOT        /* TOTAL AM WEIGHTED FOR ROOT DISTRIBUTION     */
     FLOAT INITIAL(0);
DCL  INDEX,      /* INDICATOR OF PHENOSTAGE PERIODS WHEN        */
                 /* ROOT DISTRIBUTION CHANGES                   */
      FIXED,
     MOISFAC     /* FACTOR WHICH TAKES INTO ACCOUNT             */
                 /* MOISTURE STRESS                             */
      FLOAT;
DCL ROOTDIST(6,8)/* APPROXIMATE ROOT DISTRIBUTIONS USED         */
                 /* TO ESTIMATE IMPACT OF AM ON FORAGE GROWTH   */
                 /* (ZONE = VSMB SOIL MOISTURE ZONE)             */
                 /*                                             */
 FLOAT STATIC INITIAL
/*ZONE                      INDEX                               */
/*      1      2      3      4      5      6      7      8      */
/*1*/(0.200, 0.175, 0.150, 0.125, 0.125, 0.100, 0.175, 0.100,
/*2*/ 0.275, 0.250, 0.213, 0.188, 0.175, 0.150, 0.250, 0.150,
/*3*/ 0.275, 0.275, 0.250, 0.250, 0.200, 0.200 ,0.275, 0.200,
/*4*/ 0.200, 0.200, 0.238, 0.263, 0.225, 0.250, 0.200, 0.250,
/*5*/ 0.050, 0.088, 0.088, 0.113, 0.150, 0.175, 0.088, 0.175,
/*6*/ 0.000, 0.013, 0.063, 0.063, 0.125, 0.125, 0.013, 0.125);
/*                                                              */
IF (LIFESTAGE<=2) THEN
   DO;
     INDEX=FLOOR(10*D)+1;
     IF INDEX>5 THEN INDEX=6;
   END;
              ELSE
   IF D<0.2 THEN INDEX=7;
           ELSE INDEX=8;
AMTOT=0;
DO J=1 TO 6;
  AMTOT=AMTOT+AM(POSN,J)*ROOTDIST(J,INDEX);
END;
IF AMTOT<CRITAM THEN MOISFAC=AMTOT/CRITAM;
              ELSE MOISFAC=1;
YACT=YPOT*MOISFAC;
AFYLDS(POSN,GROWTH)=AFYLDS(POSN,GROWTH)+YACT;
YIELD(POSN)=YIELD(POSN)+YACT;
```

```
END SIMFOY;
/*                                                                    */
/* + + + + + + + +END OF SIMFOY+ + + + + + + + + + + + + + + + + + + +*/
/*                                                                    */
/* + + + + + + + + + + +FEDDES+ + + + + + + + + + + + + + + + + + + + */
/*                                                                    */
/* FEDDES - CROP MODEL DEVELOPED BY FEDDES, KOWALIK,                  */
/* AND ZARADANY (1979) AS PRESENTED AND MODIFIED BY                   */
/* SLABBERS ET AL. (1979).  THE FEDDES IS BASED ON                    */
/* THE WAGENINGEN METHOD                                              */
/* THIS MODEL IS USED TO ESTIMATE ALFALFA YIELDS                      */
/*                                                                    */
FEDDES:PROCEDURE;
CALL BETA; /* CALCULATE WHAT % IS HARVESTABLE                         */
YACT=YPOT*ET(POSN);
AFYLDS(POSN,GROWTH)=AFYLDS(POSN,GROWTH)+YACT;
YIELD(POSN)=YIELD(POSN)+YACT;
/*                                                                    */
/* . . . . . . . . . BETA . . . . . . . . . . . . . . . . . . . . .  */
/*                                                                    */
/* BETA CALCULATES THE PROPORTION OF TOTAL YIELD WHICH IS             */
/* ABOVE GROUND AND THEREFORE HARVESTABLE.                            */
/*                                                                    */
BETA:PROCEDURE;
DCL   Y                /* TOTAL YIELD (t/ha DRY MATTER)               */
      FLOAT;
Y=YIELD(POSN)/1000.0*0.85;
IF Y > 10.7 THEN
  TOPPOR(POSN)=0.935;
           ELSE
  TOPPOR(POSN)=0.28572+0.321513*Y-0.067883*Y**2+
                0.00633818*Y**3-0.000212327*Y**4;
END BETA;
/*                                                                    */
/* . . . . . . . . END OF BETA . . . . . . . . . . . . . . . . . . . .*/
/*                                                                    */
END FEDDES;
/*                                                                    */
/* + + + + + + + + END OF FEDDES+ + + + + + + + + + + + + + + + + + + */
/*                                                                    */
END YLDEST;
/*                                                                    */
/******************END OF YLDEST**************************************/
/*                                                                    */
/*                                                                    */
/*********************************************************************/
/*                                                                    */
/*                                 IRRIGAT                            */
/*                                                                    */
/* IRRIGAT HANDLES MOVEMENT OF THE IRRIGATION SYSTEM THROUGH          */
/* THE FIELD, AS WELL AS SCHEDULING IRRIGATION                        */
/*                                                                    */
 IRRIGAT:PROCEDURE;
DCL  AMOUNT           /* AMOUNT OF THE CURRENT IRRIGATION (mm)        */
       FLOAT STATIC;
DCL (PLANAMT,         /* THE ANTICIPATED IRRIGATION NEED (mm)         */
     VOL)             /* NET VOLUME OF WATER USED FOR THIS DAY'S      */
                      /* IRRIGATION (ha-mm)                           */
       FLOAT;
DCL (L,               /* ROUNDED LIFESTAGE FOR PURPOSES OF            */
                     /* OF IRRIGATION SCHEDULING                             */
     P)              /* LOCATION USED FOR SCHEDULING IRRIGATIONS             */
      FIXED;
DCL GOFORIT          /* IS IRRIGATION REQUIRED TODAY FLAG                    */
     BIT(1);
IF CROP = WHEAT THEN
  L=CEIL(PHENOSTAGE+0.25);
                     ELSE  /* ALFALFA */
  L=CEIL(PHENOSTAGE*2+0.25);
IF L > 5 THEN L=5;
IF CROP = ALFALFA THEN
  DO;                                                                        */
    /*                                                                       */
    /* IRRIGATION INTERRUPTED FOR 1 WEEK RIGHT AFTER CUTTING                 */
    /*
    IF LIFESTAGE > 2 & GADAYS(GROWTH) < 8 THEN GOTO NDIRR;                   */
    /*                                                                       */
    /* IRRIGATION INTERRUPTED IF CLOSE TO CUTTING TIME                       */
    /*
    IF D > 0.95 THEN GOTO NDIRR;
  END;                                                                       */
                    ELSE   /*   WHEAT                                        */
  /*                                                                         */
  /* FOR WHEAT: NO IRRIGATIONS DURING CROP RIPENING PERIOD                   */
  /*
  IF CROP=WHEAT & PHENOSTAGE >= 4.50 THEN GOTO NDIRR;                        */
/*                                                                           */
/* NO IRRIGATIONS ARE ALLOWED BEFORE FIRSTDAY OR AFTER LASTDAY               */
/*
IF (DAY <= FIRSTDAY) | (DAY >= LASTDAY) THEN GOTO NDIRR;
IF IRRTYPE = 1 THEN CALL CNTRPIV;
                   ELSE /* MULTSET ONLY NEEDS UPDATING ONCE                  */
  IF POSN = 2 THEN CALL MULTSET;                                             */
/*
/* + + + + + + + + + CNTRPIV + + + + + + + + + + + + + + + + + +*/
                                                                             */
/*                                                                           */
/* CNTRPIV HANDLES A CENTRE PIVOT SYSTEM WHICH IS EITHER                     */
/* STATIONARY OF TOWABLE.  FIELD 1 HAS PRIORITY OVER FIELD 2                 */
/* WHICH HAS PRIORITY OVER FIELD 3.                                          */
/*
CNTRPIV:PROCEDURE;
DCL  (PREVSTAT,          /* PREVIOUS DAY'S STATUS (REV.FRACTION)             */
      AVGREVRAT)         /* REVOLUTION RATE (REVS/d) MIDWAY BETWEEN          */
                         /* MINIMUM AND MAXIMUM                              */

       FLOAT;
DCL   REVS               /* REVS NEEDED FOR CURRENT IRRIGATION               */
       FLOAT STATIC;                                                         */
DCL   REVRATE            /* REVS PER DAY
       FLOAT STATIC;
P=POSN;                   /* SCHEDULE FOR EACH FIELD INDEPENDENTLY           */
IF IDLE THEN
  DO;
    CALL SCHEDUL;
    IF ¬GOFORIT THEN GOTO SITTING;
                 ELSE  /* IRRIGATION IS REQUIRED                    */
      DO;
        NUMIRR=NUMIRR+1;
        IDLE=FALSE;
        AVGREVRAT=(MINRATE+MAXRATE)/2.0;
        REVS=CEIL(PLANAMT/(SYSRAT/SETAREA/AVGREVRAT));
      IF REVS < 1.0 THEN
        DO;
          IDLE=FALSE;
          GOTO SITTING;
        END;
      REVRATE=(SYSRAT/SETAREA/PLANAMT)*REVS;
      IF REVRATE > MAXRATE THEN REVRATE=MAXRATE;
      AMOUNT=SYSRAT/SETAREA/REVRATE;
      /*                                                       */
      /* IF THE PIVOT IS THE OTHER FIELD ONE DAY IS            */
      /* WASTED MOVING THE SYSTEM TO THIS FIELD                */
      /* THE PIVOT CAN NOT BE MOVED IF THE FIELD IS NOT        */
      /* TRAGABLE                                              */
      /*                                                       */
      IF IRRH2O > 0.0 THEN  /* IRRIGATION ALREADY TODAY        */
        DO;
          NUMIRR=NUMIRR-1;
          IDLE=TRUE;
          GOTO SITTING;
        END;
      IF POSN = WHEREIS THEN   /* IRRIGATE THIS DAY             */
        DO;
          IRRGTNS(NUMIRR,1)=DAY;
          IRRGTNS(NUMIRR,2)=AMOUNT*REVS;
          IRRGTNS(NUMIRR,3)=POSN-1;
          GOTO IRRGTN;
        END;
                        ELSE
        DO:
          DO J=1 TO 3;
            IF AM(WHEREIS,J) >= TRACAM(J) THEN /*TRACTOR STUCK*/
              DO;
                NUMIRR=NUMIRR-1;
                IDLE=TRUE;
                GOTO SITTING;
              END;
          END;
          WHEREIS=POSN;
          IRRLAB=IRRLAB+MOVTIM;
          /*                                                   */
          /* PIVOT HAS BEEN MOVED TO OTHER FIELD AND           */
          /* IRRIGATION WILL START TOMORROW                    */
          /*                                                   */
          IRRGTNS(NUMIRR,1)=DAY+1;
          IRRGTNS(NUMIRR,2)=AMOUNT*REVS;
          IRRGTNS(NUMIRR,3)=POSN-1;
          GOTO SITTING;
        END;
    END;
END;
      ELSE                 /* SYSTEM IS ALREADY BUSY           */
IF POSN ¬= WHEREIS THEN GOTO SITTING;
                     ELSE   /* IRRIGATE THIS DAY IF IN FIELD   */
  IRRGTN:DO;
    PREVSTAT=STATUS;
    STATUS=STATUS+REVRATE;
    IRRDAYS=IRRDAYS+1;
    IRRLAB=IRRLAB+1.0;
    IRRH2O=AMOUNT;
    IF STATUS < REVS THEN
```

```
        DO;
          IRRAREA=REVRATE*SETAREA;
          /*                                                  */
          /* IRRIGATION OCCURS WHEN LATERAL CROSSES            */
          /* STARTPOSITION BOUNDARY                            */
          /*                                                  */
          IRR(POSN)=(CEIL(STATUS)-CEIL(PREVSTAT))*AMOUNT;
        END;
                      ELSE    /* FINISHED CURRENT IRRIGATION   */
        DO;
          IRR(POSN)=(CEIL(REVS)-CEIL(PREVSTAT))*AMOUNT;
          IRRAREA=(REVS-PREVSTAT)*SETAREA;
          STATUS=0.0;
          REVS=0.0;
          IDLE=TRUE;
        END;
      TOTIREA=TOTIREA+IRRAREA;
      VOL=IRRAREA*IRRH2O;
      RESERV=RESERV-VOL/IRREFF;
      TOTH2O=TOTH2O+VOL;
    END;
SITTING:END CNTRPIV;
/*                                                           */
/* + + + + + + +END OF CNTRPIV+ + + + + + + + + + + + + + + + + */
/*                                                           */
/* + + + + + + + +MULTSET + + + + + + + + + + + + + + + + + + + */
/*                                                           */
/* MULTSET HANDLES THE MOVEMENT OF A IRRIGATION SYSTEM WITH   */
/* DISTINCT SETS NEEDED TO IRRIGATE ONE FIELD.  THIS COULD BE */
/* A SIDE ROLL SYSTEM, A HAND MOVE SYSTEM, OR A TRAVELLING    */
/* GUN (WITH APPROPIATE SYSTEM PARAMETERS FOR EACH TYPE OF    */
/* SYSTEM).                                                  */
/* IRRIGATIONS ARE DELAYED IF RAIN SINCE THE IRRIGATION STARTED */
/* EXCEEDS 25% OF THE PLANNED IRRIGATION AMOUNT.             */
/*                                                           */
MULTSET:PROCEDURE;
DCL  PREVSTAT        /* YESTERDAY'S STATUS (SET.FRACTION)     */
                     /* TO MOVE THE SYSTEM                    */
      FLOAT;
DCL (DLYSETS,        /* NUMBER OF SETS DONE EACH DAY          */
     SETTIM)         /* HOURS FOR ONE SET INCLUDING MOVE TIME */
      FLOAT STATIC;
DCL  (YST,           /* SET SYSTEM STARTED YESTERDAY          */
      NOW)           /* SET SYSTEM FINISHED THIS DAY          */
       FIXED;
/*                                                           */
/* ONLY NEED TO UPDATE SYSTEM ONCE FOR IRRIGATED FIELD       */
/*                                                           */
P=2;                 /* SCHEDULING BASED ON SOIL AT FIRST SET */
IF IDLE THEN CALL SCHEDUL;
       ELSE GOTO IRRGTNG;
IF ¬GOFORIT THEN GOTO NDMS;        /* NO IRRIGATION NEEDED    */
          ELSE
  /*                                                         */
  /* CALCULATE HOW MUCH AND HOW LONG TO IRRIGATE EACH SET    */
  /*                                                         */
  DO;
    NUMIRR=NUMIRR+1;
    AMOUNT=PLANAMT;
    SETTIM=AMOUNT/SYSRAT+MOVTIM;
```

```
   /*                                                            */
   /* SEE THAT SETTIMES NEITHER TOO SLOW OR TOO FAST             */
   /*                                                            */
    IF DLYSETS > MAXRATE THEN DLYSETS=MAXRATE;
                         ELSE
     IF DLYSETS < MINRATE THEN DLYSETS=MINRATE;
    SETTIM=24.0/DLYSETS;
    AMOUNT=SYSRAT*(SETTIM-MOVTIM);
    IRRGTNS(NUMIRR,1)=DAY;
    IRRGTNS(NUMIRR,2)=AMOUNT;
    IDLE=FALSE;
  END;
IRRGTNG::
  IF IRRAIN >= 0.25*AMOUNT THEN
    DO;
      /*                                                         */
      /* SYSTEM IS DELAYED TO TAKE ADVANTAGE OF RAIN             */
      /* WHICH HAS FALLEN                                        */
      /*                                                         */
      DELAY=FLOOR(IRRAIN/(0.85*DRYPET));
      IRRAIN=0.0;
    END;
    /*                                                           */
    /* ONLY 90% OF RAIN OVER  5 mm IS COUNTED TO DETERMINE       */
    /* IF THE SYSTEM SHOULD BE DELAYED                           */
    /*                                                           */
    IF RAIN > 5.0 THEN IRRAIN=IRRAIN+0.9*RAIN;
    IF DELAY > 0 THEN DELAY=DELAY-1;
                 ELSE     /* IRRIGATE */
      DO;
        PREVSTAT=STATUS;
        STATUS=STATUS+DLYSETS;
        IRRLAB=IRRLAB+MOVTIM*DLYSETS;
        IRRDAYS=IRRDAYS+1;
        /*                                                       */
        /* DETERMINE WHICH SET WAS IRRIGATED THIS DAY. DEFINED   */
        /* WHEN LATERAL CROSSES INTO NEXT SET                    */
        /*                                                       */
        YST=FLOOR(PREVSTAT);
        NOW=FLOOR(STATUS);
        WHEREIS=0;
        IF YST < FIRSTSET & NOW >= FIRSTSET THEN WHEREIS=2;
                                            ELSE
          IF YST < MIDSET & NOW >= MIDSET THEN WHEREIS=3;
        IF  NOW >= LASTSET THEN
          /*                                                     */
          /* FINISHED CURRENT IRRIGATION THIS DAY                */
          /*                                                     */
          DO;
            WHEREIS=4;
            IRRAREA=(LASTSET-PREVSTAT)*SETAREA;
            IRRH2O=AMOUNT;
            IRRLAB=IRRLAB+MOVTIM*2.0; /* MOVE BACK TO FIRST SET */
            /*                                                   */
            /* RESET SYSTEM                                      */
            /*                                                   */
            STATUS=0.0;
            IDLE=TRUE;
            IRRAIN=0.0;
          END;
```

```
                      ELSE /* AT INTERMEDIATE FIELD POSITION */
         DO;
           IRRAREA=DLYSETS*SETAREA;
           IRRH2O=AMOUNT;
         END;
       TOTIREA=TOTIREA+IRRAREA;
       VOL=IRRAREA*IRRH2O;
       RESERV=RESERV-VOL/IRREFF;
       TOTH2O=TOTH2O+VOL;
       IF WHEREIS > 1 THEN IRR(WHEREIS)=AMOUNT;
     END;
NDMS: END MULTSET;                                         */
/*                                                          
/*+ + + + + + + + + +END OF MULTSET+ + + + + + + + + + + + + + +*/
/*                                                         */
/*                                                         */
/*+ + + + + + + + + + SCHEDUL + + + + + + + + + + + + + + + + + + */
/*                                                         */
/* SCHEDULE SCHEDULES THE IRRIGATION BASED ON THE SOIL     */
/* MOISTURE AT THE FIELD POSITION SPECIFIED                */
/*                                                         */
SCHEDUL:PROCEDURE;
DCL (MOISACT,       /* TOTAL ACTUAL MOISTURE IN THE ROOTING    */
                    /* ZONE (mm)                               */
     MINAMT,        /* MINIMUM APPLICATION DEPTH FOR A COMPLETE */
                    /* IRRIGATION                              */
     MINREQ,        /* MINIMUM  QUANTITY OF WATER REQUIRED TO  */
                    /* COMPLETE THE MINIMUM IRRIGATION (ha-mm) */
     PLANREQ,       /* THE REQUIRED QUANTITY OF WATER TO       */
                    /* COMPLETE THE PLANNED IRRIGATION (ha-mm) */
     AMTLIM,        /* LIMIT ON THE DEPTH (mm) OF ONE IRRIGATION*/
     REQLIM)        /* CURRENT CONTENTS OF THE RESERVOIR AVAIL- */
                    /* ABLE FOR NET IRRIGATION (ha-mm)         */

      FLOAT;
MOISACT=0.0;
DO J=1 TO ROOTDEPTH(L);
  MOISACT=MOISACT+SM(P,J);
END;
IF MOISACT > MINMOIS(L) THEN GOFORIT=FALSE;
                      ELSE
   DO;
     GOFORIT=TRUE;
     PLANAMT=OPTMOIS(L)-MOISACT;
     REQLIM=RESERV*IRREFF;                                    */
     /*                                                       */
     /* ADJUST IRRIGATION IF THERE IS WATER LIMITATIONS       */
     /*                                                       */
     IF IRRTYPE = 1 THEN  /* CENTRE PIVOT                     */
       DO;
         MINAMT=SYSRAT/MAXRATE/SETAREA;
         MINREQ=MINAMT*SETAREA;
         PLANREQ=PLANAMT*SETAREA;
         AMTLIM=REQLIM/SETAREA;
      END;
                  ELSE  /* MULTIPLE SET                       */
      DO;
        MINAMT=SYSRAT*24.0/MAXRATE;
        MINREQ=MINAMT*FLDSIZ;
        PLANREQ=PLANAMT*FLDSIZ;
        AMTLIM=REQLIM/FLDSIZ;
     END;
  IF REQLIM < MINREQ THEN GOTO NDIRR;
                      ELSE
    IF PLANREQ > REQLIM THEN PLANAMT=AMTLIM;
 END;
END SCHEDUL;
/*                                                               */
/*+ + + + + +END OF SCHEDUL+ + + + + + + + + + + + + + + + + + ++*/
/*                                                               */
NDIRR:END IRRIGAT;
/*                                                               */
/*****************END OF IRRIGAT *********************************/
/*                                                               */
/*****************************************************************/
/*                                                               */
/*                    DAYOUT                                     */
/*                                                               */
/* DAYOUT SUMMARIZES DAILY EVENTS AND LOADS THEM INTO            */
/* ARRAY EVENTS                                                  */
/*                                                               */
DAYOUT:PROCEDURE;
DCL (IRRET,      /* AVERAGE ET ON IRRIGATED AREA                 */
  IRRYLD,        /* AVERAGE YIELD (kg/ha) FOR IRRIGATED AREA     */
   MSF(4),       /* MOISTURE STRESS FACTOR FOR EACH POSN         */
   EVENTS(11),   /* DAILY EVENTS                                 */
   DRYSM,        /* DRYLAND AM IN ENTIRE ROOT ZONE               */
   IRRSM)        /* IRRIGATED SM IN ENTIRE ROOT ZONE             */
    FLOAT;
IRRYLD=0.0;
IF CROP = WHEAT THEN
 DO;
    IF GSDAYS > 0 THEN
      DO;
        EVENTS(6)=YIELD(DRY)*WMSF(DRY);
        DO I=2 TO NDPOSN;
          IRRYLD=IRRYLD+YIELD(I)*WMSF(I);
        END;
      END;
                  ELSE    /* NO YIELD YET  */
   EVENTS(6)=0.0;
  END;
                ELSE  /* ALFALFA       */
 DO;
    IF GADAYS(GROWTH) > 0 THEN
      DO;
        IF YLDMETH = 1 THEN  /* SIMFOY   */
          DO;
            EVENTS(6)=AFYLDS(DRY,GROWTH);
            DO I=2 TO NDPOSN;
              IRRYLD=IRRYLD+AFYLDS(I,GROWTH);
            END;
          END;
                       ELSE  /* FEDDES   */
          DO;
            EVENTS(6)=AFYLDS(DRY,GROWTH)*TOPPOR(DRY);
            DO I=2 TO NDPOSN;
              IRRYLD=IRRYLD+AFYLDS(I,GROWTH)*TOPPOR(I);
            END;
          END;
      END;
```

```
                          ELSE  /* NO YIELD YET  */
      EVENTS(6)=0.0;
  END;
EVENTS(1)=RAIN;
EVENTS(2)=PET;
EVENTS(3)=PHENOSTAGE;
DRYSM=0.0;
DO J=1 TO 6;
  DRYSM=DRYSM+SM(DRY,J);
END;
EVENTS(4)=DRYSM;
EVENTS(5)=ET(DRY);
EVENTS(7)=IRRAREA;
EVENTS(8)=IRRH2O;
IRRET=0.0;
IRRSM=0.0;
DO I=2 TO NDPOSN;
  IRRET=IRRET+ET(I);
  DO J=1 TO 6;
    IRRSM=IRRSM+SM(I,J);
  END;
END;
EVENTS(9)=IRRSM/NIP;
EVENTS(10)=IRRET/NIP;
EVENTS(11)=IRRYLD/NIP;
PUT SKIP FILE(OYR) EDIT(DAY,(EVENTS(JJ) DO JJ=1 TO 11))
  (X(1),F(3),F(5,1),F(5,1),F(6,2),F(7,1),F(5,1),X(1),F(6),
   F(7,1),F(7,1),X(2),2(F(5,1)),X(1),F(6));
END DAYOUT;
/*                                                              */
/***************END OF DAYOUT ***********************************/
/*                                                              */
/****************************************************************/
/*                                                              */
/*                 EVALUAT                                      */
/*                                                              */
/* EVALUATE CALCULATES AND OUTPUTS ONE SEASON'S                 */
/* RESULTS.                                                     */
/*                                                              */
EVALUAT:PROCEDURE;
DCL (NETAPP,        /* SEASONAL NET APPLICATION (mm)                */
     VARCOST,       /* VARIABLE IRRIGATION COSTS ($/ha)             */
     TOTCOST,       /* SEASONAL COST OF IRRIGATION ($/ha)           */
     TOTBENFIT,     /* SEAONAL BENEFITS OF IRRIGATION ($/ha)        */
     NETBENFIT,     /* SEASONAL NET BENEFITS OF IRRIGATION I.E.     */
                    /*   (TOTBENFIT-TOTCOST)  ($/ha)                */
     YLDINC,        /* YIELD INCREASE DUE TO IRRIGATION (kg/ha)     */
     DRYCUT1,       /* DRYLAND FIRST ALFALFA CUT YIELD              */
     DRYCUT2,       /*    "   SECOND     "    "    "                */
     IRRCUT1,       /* AVERAGE IRRIGATED FIRST ALFALFA CUT YIELD    */
     IRRCUT2,       /*    "        "        SECOND    "    "    " */
     DRYYLD,        /* DRYLAND YIELD (kg/ha)                        */
     IRRYLD,        /* AVERAGE IRRIGATED YIELD (kg/ha)              */
     DRYET,         /* DRYLAND GROWING SEASON ET (mm)               */
     IRRET,         /* AVERAGE IRRIGATED GROWING SEASON ET (mm)     */
     DTET,          /* DRYLAND TOTAL ET (mm)                        */
     ITET,          /* IRRIGATED TOTAL ET (mm)                      */
     TIRRRUN,       /* AVERAGE SURFACE RUNOFF FROM IRRIGATED LAND   */
     TIRRPERC)      /*    "   DEEP PERCOLATION   "     "     "      */
      FLOAT;
```

```
/*                                                              */
/* CALCULATE DRYLAND AND AVERAGE IRRIGATED OCTOBER 15 SOIL      */
/* MOISTURE, CROP ET, TOTAL ET, TOTAL RUNOFF, AND TOTAL DEEP    */
/* PERCOLATION                                                  */
/*                                                              */
DRYENDSM=0.0;
IRRENDSM=0.0;
DO J=1 TO 6;
  DRYENDSM=DRYENDSM+SM(1,J);
END;
DO I=2 TO NDPOSN;
  DO J= 1 TO 6;
    IRRENDSM=IRRENDSM+SM(I,J);
  END;
END;
IRRENDSM=IRRENDSM/NIP;
TIRRRUN=0.0;
TIRRPERC=0.0;
IRRET=0.0;
ITET=0.0;
DO I=2 TO NDPOSN;
  TIRRRUN=TIRRRUN+TOTRUNOFF(I);
  TIRRPERC=TIRRPERC+TOTDEEPERC(I);
  IRRET=IRRET+GSET(I);
  ITET=ITET+TOTET(I);
END;
TIRRRUN=TIRRRUN/NIP;
TIRRPERC=TIRRPERC/NIP;
IRRET=IRRET/NIP;
ITET=ITET/NIP;
DTET=TOTET(1);
DRYET=GSET(1);
/*                                                              */
/* CALCULATE FINAL YIELDS                                       */
/*                                                              */
IF CROP = WHEAT THEN
  DO;
    IRRYLD=0.0;
    DO I=2 TO NDPOSN;
      IRRYLD=IRRYLD+YIELD(I)*WMSF(I);
    END;
    /*                                                          */
    /* YIELDS < 500.0 Kg/ha ARE ASSUMED NOT WORTH GOING AFTER   */
    /*                                                          */
    DRYYLD=YIELD(DRY)*WMSF(DRY);
    IF DRYYLD < 500.0 THEN DRYYLD=0.0;
    IRRYLD=IRRYLD/NIP;
    IF IRRYLD < 500.0 THEN IRRYLD=0.0;
  END;
                ELSE    /* ALFALFA                              */
  DO;
    IRRCUT1=0.0;
    IRRCUT2=0.0;
    DRYYLD=0.0;
    IRRYLD=0.0;
    IF YLDMETH=1 THEN    /* SIMFOY                              */
      DO;
        DRYCUT1=AFYLDS(1,1);
        DRYCUT2=AFYLDS(1,2);
        DO I=2 TO NDPOSN;
```

```
          IRRCUT1=IRRCUT1+AFYLDS(I,1);
          IRRCUT2=IRRCUT2+AFYLDS(I,2);
        END;
      END;
                ELSE         /* FEDDES                           */
      DO;
        DRYCUT1=AFYLDS(1,1)*TOPPOR(1);
        DRYCUT2=AFYLDS(1,2)*TOPPOR(1);
        DO I=2 TO NDPOSN;
          IRRCUT1=IRRCUT1+AFYLDS(I,1)*TOPPOR(I);
          IRRCUT2=IRRCUT2+AFYLDS(I,2)*TOPPOR(I);
        END;
      END;
    IRRCUT1=IRRCUT1/NIP;
    IRRCUT2=IRRCUT2/NIP;
    /*                                                           */
    /* ASSUME NOT WORTHWHILE TO TAKE SECOND CUT IF < 1100 kg/ha */
    /*                                                           */
    IF DRYCUT2 < 1100.0 THEN DRYCUT2=0.0;
    IF IRRCUT2 < 1100.0 THEN IRRCUT2=0.0;
    DRYYLD=DRYCUT1+DRYCUT2;
    IRRYLD=IRRCUT1+IRRCUT2;
  END;
/*                                                               */
/* CALCULATE RETURNS AT THE END OF THE SEASON                    */
/*                                                               */
YLDINC=IRRYLD-DRYYLD;
NETAPP=TOTH2O/FLDSIZ;
TOTBENFIT=YLDINC*CROPVAL;
VARCOST=NETAPP*(HEADRAT*XTRAHEAD+LABRAT+NRGRAT)+
        HARVCOST*YLDINC+FERTCOST;
TOTCOST=FIXDCOST+VARCOST;
NETBENFIT=TOTBENFIT-TOTCOST;
/*                                                               */
/* PUT OUT ANNUAL DATA INTO FILE OYR                             */
/*                                                               */
PUT SKIP(3) FILE(OYR) EDIT('SOIL MOISTURE')(X(4),A);
PUT SKIP FILE(OYR) EDIT('APRIL 9:','DRYLAND=',DRYBEGSM,
                    ' mm','IRRIGATED=',IRRBEGSM,' mm')
               (X(10),A,COL(31),A,F(4,0),A,X(10),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('OCT 15:','DRYLAND=',DRYENDSM,' mm',
                           'IRRIGATED=',IRRENDSM,' mm')
               (X(10),A,COL(31),A,F(4,0),A,X(10),A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('TOTAL PRECIPITATION APRIL 9 TO',
              ' OCT 15=',TOTRAIN,' mm')(X(4),A,A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('PRECIPITATION DURING ACTIVE GROWING',
              ' SEASON=',GSRAIN,' mm')(X(4),A,A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('TOTAL ET FROM APRIL 9 TO OCT 15')
                       (X(4),A);
PUT SKIP FILE(OYR) EDIT('DRYLAND=',DTET,' mm')
                       (X(10),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('IRRIGATED=',ITET,' mm')
                       (X(10),A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('TOTAL SURFACE RUNOFF')(X(4),A);
PUT SKIP FILE(OYR) EDIT('DRYLAND=',TOTRUNOFF(1),' mm')
                       (X(10),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('IRRIGATED=',TIRRRUN,' mm')
                           (X(10),A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('TOTAL DEEP PERCOLATION')(X(4),A);
PUT SKIP FILE(OYR) EDIT('DRYLAND=',TOTDEEPERC(1),' mm')
```

```
                      (X(4),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('IRRIGATED=',TIRRPERC,' mm')
                      (X(4),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('DEGREE DAYS ( > 5C ) DURING ACTIVE ',
                       'GROWING SEASON= ',GSDD)
                      (X(4),A,A,F(5,0));
PUT SKIP FILE(OYR) EDIT('GROWTH STARTED ON DAY= ',BEGDAY,
                       ' AND CONTINUED FOR ',
                  GSDAYS,' d')(X(4),A,F(3,0),A,F(3,0),A);
PUT SKIP(2) FILE(OYR) EDIT('IRRIGATIONS')(X(4),A);
IF NUMIRR < 1 THEN                /* THERE WERE SOME IRRIGATIONS */
 PUT SKIP FILE(OYR) EDIT('NUMBER=',NUMIRR)(X(10),A,F(2,0));
             ELSE
 DO;
  IF IRRTYPE = 1 & NDPOSN > 2 THEN/* TOWABLE CENTRE PIVOT      */
   DO;
    PUT SKIP FILE(OYR) EDIT('NUMBER','DAY STARTED',
                           'AMOUNT mm','FIELD')
                          (X(8),A,COL(20),A,COL(40),A,COL(60),A);

    DO J=1 TO NUMIRR;
     PUT SKIP FILE(OYR) EDIT(J,IRRGTNS(J,1),IRRGTNS(J,2),
                            IRRGTNS(J,3))
    (COL(12),F(2,0),COL(25),F(3,0),COL(42),F(5,1),COL(62),F(1,0));
    END;
   END;
                           ELSE
                                                              */
   /*
   /* STATIONARY CENTRE PIVOT OR MULTIPLE SET IRRIGATION SYSTEM */
                                                              */
   /*
   DO:
    PUT SKIP FILE(OYR) EDIT('NUMBER','DAY STARTED','AMOUNT mm')
                          (X(8),A,COL(20),A,COL(40),A);

    PUT SKIP FILE(OYR);
    DO J=1 TO NUMIRR;
     PUT SKIP FILE(OYR) EDIT(J,IRRGTNS(J,1),IRRGTNS(J,2))
             (COL(12),F(2,0),COL(25),F(3,0),COL(42),F(5,1));

    END;
   END;
 END;
PUT SKIP(2) FILE(OYR) EDIT('NET APPLICATION DEPTH=',NETAPP,' mm')
                      (X(11),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('GROSS WATER USED=',(TOTH2O/IRREFF),
                       ' ha-mm')
                      (X(10),A,F(8,0),A);
PUT SKIP FILE(OYR) EDIT('LABOUR=',IRRLAB,' HOURS')
                      (X(10),A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('YIELDS')(X(4),A);
PUT SKIP FILE(OYR) EDIT('DRYLAND=',DRYYLD,' kg/ha')
                      (X(10),A,F(5,0),A);
PUT SKIP FILE(OYR) EDIT('IRRIGATED=',IRRYLD,' kg/ha')
                      (X(10),A,F(5,0),A);
PUT SKIP FILE(OYR) EDIT('INCREASE=',YLDINC,' kg/ha')
                      (X(10),A,F(5,0),A);
PUT SKIP FILE(OYR) EDIT('=$',TOTBENFIT,'/ha')(X(18),A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('VARIABLE COST=$',VARCOST,'/ha')
                         (X(4),A,F(4,0),A);
PUT SKIP FILE(OYR) EDIT('TOTAL COSTS=$',TOTCOST,'/ha')
                      (X(4),A,F(4,0),A);
PUT SKIP(2) FILE(OYR) EDIT('NET BENEFIT=$',NETBENFIT,'/ha')
                         (X(4),A,F(4,0),A);
```

```
PUT SKIP FILE(DYR) EDIT('=$',(NETBENFIT*FLDSIZ))(X(15),A,F(6,0));
PUT SKIP FILE(DYR);
/*                                                                */
/* CALCULATE SUMS AND SUMS OF SQUARES FOR STATISTICS              */
/*                                                                */
SUMSM(1)=SUMSM(1)+DRYENDSM;
SSQSM(1)=SSQSM(1)+DRYENDSM*DRYENDSM;
SUMSM(2)=SUMSM(2)+IRRENDSM;
SSQSM(2)=SSQSM(2)+IRRENDSM*IRRENDSM;
SUMRUN(1)=SUMRUN(1)+TOTRUNOFF(1);
SSQRUN(1)=SSQRUN(1)+TOTRUNOFF(1)*TOTRUNOFF(1);
SUMRUN(2)=SUMRUN(2)+TIRRRUN;
SSQRUN(2)=SSQRUN(2)+TIRRRUN*TIRRRUN;
SUMPERC(1)=SUMPERC(1)+TOTDEEPERC(1);
SSQPERC(1)=SSQPERC(1)+TOTDEEPERC(1)*TOTDEEPERC(1);
SUMPERC(2)=SUMPERC(2)+TIRRPERC;
SSQPERC(2)=SSQPERC(2)+TIRRPERC*TIRRPERC;
SUMET(1)=SUMET(1)+DRYET;
SUMET(2)=SUMET(2)+IRRET;
SSQET(1)=SSQET(1)+DRYET*DRYET;
SSQET(2)=SSQET(2)+IRRET*IRRET;
SUMRET(1)=SUMRET(1)+DRYET/GSPET;
SSQRET(1)=SSQRET(1)+DRYET/GSPET*DRYET/GSPET;
SUMRET(2)=SUMRET(2)+IRRET/GSPET;
SSQRET(2)=SSQRET(2)+IRRET/GSPET*IRRET/GSPET;
SUMTET(1)=SUMTET(1)+DTET;
SSQTET(1)=SSQTET(1)+DTET*DTET;
SUMTET(2)=SUMTET(2)+ITET;
SSQTET(2)=SSQTET(2)+ITET*ITET;
SUMYLD(1)=SUMYLD(1)+DRYYLD;
SSQYLD(1)=SSQYLD(1)+DRYYLD*DRYYLD;
SUMYLD(2)=SUMYLD(2)+IRRYLD;
SSQYLD(2)=SSQYLD(2)+IRRYLD*IRRYLD;
IF CROP =ALFALFA THEN
  DO;
    SUMCUT1(1)=SUMCUT1(1)+DRYCUT1;
    SSQCUT1(1)=SSQCUT1(1)+DRYCUT1*DRYCUT1;
    SUMCUT1(2)=SUMCUT1(2)+IRRCUT1;
    SSQCUT1(2)=SSQCUT1(2)+IRRCUT1*IRRCUT1;
    SUMCUT2(1)=SUMCUT2(1)+DRYCUT2;
    SSQCUT2(1)=SSQCUT2(1)+DRYCUT2*DRYCUT2;
    SUMCUT2(2)=SUMCUT2(2)+IRRCUT2;
    SSQCUT2(2)=SSQCUT2(2)+IRRCUT2*IRRCUT2;
  END;
SUMINC=SUMINC+YLDINC;
SSQINC=SSQINC+YLDINC*YLDINC;
SUMNET=SUMNET+NETAPP;
SSQNET=SSQNET+NETAPP*NETAPP;
SUMNMIRR=SUMNMIRR+NUMIRR;
SSQNMIRR=SSQNMIRR+NUMIRR*NUMIRR;
SUMLAB=SUMLAB+IRRLAB;
SSQLAB=SSQLAB+IRRLAB*IRRLAB;
SUMVAR=SUMVAR+VARCOST;
SSQVAR=SSQVAR+VARCOST*VARCOST;
SUMPRF=SUMPRF+NETBENFIT;
SSQPRF=SSQPRF+NETBENFIT*NETBENFIT;
/*                                                                */
/* OUTPUT YEARLY SUMMARY                                          */
/*                                                                */
IF CROP = WHEAT THEN
```

```
 PUT SKIP FILE(OUT) EDIT(YEAR,GSRAIN,DRYBEGSM,DRYET,DRYYLD,
     IRRBEGSM,NETAPP,NUMIRR,IRRET,IRRYLD,VARCOST,NETBENFIT)
     (X(4),F(2,0),F(6,0),F(5,0),F(6,0),F(7,0),F(5,0),X(1),F(5,0),
      X(2),F(2,0),F(5,0),F(7,0),F(7,1),F(7,1));
              ELSE  /* ALFALFA */
 PUT SKIP FILE(OUT) EDIT(YEAR,GSRAIN,DRYBEGSM,DRYET,DRYCUT1,
       DRYCUT2,IRRBEGSM,NETAPP,NUMIRR,IRRET,IRRCUT1,IRRCUT2,
       VARCOST,NETBENFIT)
       (X(2),F(2,0),F(4,0),F(5,0),F(4,0),X(1),F(5,0),F(6,0),X(1),
        2(F(4,0)),X(2),F(2,0),F(4,0),X(2),F(5,0),F(6,0),
        F(7,1),F(7,1));
END EVALUAT;                                                          */
/*
/*******************END OF EVALUAT*********************************/
/*                                                                    */
/******************************************************************/
/*                                                                    */
/*                           SUMRIZ                                   */
/*                                                                    */
/* SUMRIZ CALCULATES AND OUTPUTS MEAN AND STANDARD DEVIATION          */
/* OF SEVERAL QUANTITIES INTO FILE OUT                                */
/*                                                                    */
SUMRIZ:PROCEDURE;
PUT SKIP(3) FILE(OUT) EDIT('DRYLAND','IRRIGATED')
                        (COL(36),A,COL(56),A);
PUT SKIP FILE(OUT) EDIT('MEAN','   SD','MEAN','   SD')
                        (COL(34),A,X(3),A,X(8),A,X(3),A):
PUT SKIP(0) FILE(OUT) EDIT((46)'_')(COL(30),A);
PUT SKIP(2) FILE(OUT) EDIT('OCT 15 SOIL MOISTURE (mm)',
                             (SUMSM(1)/N),SD(SSQSM(1),SUMSM(1)),
                             (SUMSM(2)/N),SD(SSQSM(2),SUMSM(2)))
                        (X(1),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('TOTAL SURFACE RUNOFF (mm)',(SUMRUN(1)/N),
                         SD(SSQRUN(1),SUMRUN(1)),(SUMRUN(2)/N),
                         SD(SSQRUN(2),SUMRUN(2)))
                      (X(1),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('DEEP PERCOLATION (mm)',(SUMPERC(1)/N),
                         SD(SSQPERC(1),SUMPERC(1)),(SUMPERC(2)/N),
                         SD(SSQPERC(2),SUMPERC(2)))
                   (X(1),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('TOTAL ET (mm)',(SUMTET(1)/N),
                         SD(SSQTET(1),SUMTET(1)),(SUMTET(2)/N),
                         SD(SSQTET(2),SUMTET(2)))
                   (X(1),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('ANNUAL CROP ET (mm)',(SUMET(1)/N),
                         SD(SSQET(1),SUMET(1)),(SUMET(2)/N),
                         SD(SSQET(2),SUMET(2)))
                   (X(1),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('ET/PET',(SUMRET(1)/N),
                         SD(SSQRET(1),SUMRET(1)),
                         (SUMRET(2)/N),SD(SSQRET(2),SUMRET(2)))
                   (X(1),A,COL(30),2(F(8,2)),X(4),2(F(8,2)));
PUT SKIP FILE(OUT) EDIT('YIELD (kg/ha)',(SUMYLD(1)/N),
                         SD(SSQYLD(1),SUMYLD(1)),(SUMYLD(2)/N),
                         SD(SSQYLD(2),SUMYLD(2)))
                   (X(1),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
 IF CROP = ALFALFA THEN
   DO;
     PUT SKIP FILE(OUT) EDIT('FIRST CUT=',(SUMCUT1(1)/N),
                         SD(SSQCUT1(1),SUMCUT1(1)),(SUMCUT1(2)/N),
                    SD(SSQCUT1(2),SUMCUT1(2)))
                (X(5),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
    PUT SKIP FILE(OUT) EDIT('SECOND CUT=',(SUMCUT2(1)/N),
                    SD(SSQCUT2(1),SUMCUT2(1)),(SUMCUT2(2)/N),
                    SD(SSQCUT2(2),SUMCUT2(2)))
                (X(5),A,COL(30),2(F(8,0)),X(4),2(F(8,0)));
  END;
PUT SKIP(3) FILE(OUT) EDIT('IRRIGATION RESULTS','MEAN','   SD')
                        (A,COL(44),A,X(3),A);
PUT SKIP(0) FILE(OUT) EDIT((56)'_')(A);
PUT SKIP(2) FILE(OUT) EDIT('YIELD INCREASE (Kg/ha)',(SUMINC/N),
                        SD(SSQINC,SUMINC))
                (X(1),A,COL(40),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('NET APPLICATION (mm)',(SUMNET/N),
                       SD(SSQNET,SUMNET))(A,COL(40),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('LABOUR (h)',(SUMLAB/N),SD(SSQLAB,SUMLAB))
                (X(1),A,COL(40),2(F(8,0)));
PUT SKIP FILE(OUT) EDIT('IRRIGATIONS/YEAR',(SUMNMIRR/N),
                       SD(SSQNMIRR,SUMNMIRR))
                (X(1),A,COL(40),2(F(8,2)));
PUT SKIP FILE(OUT) EDIT('TOTAL ANNUAL COSTS ($/ha)',
                       (FIXDCOST+SUMVAR/N),
                       SD(SSQVAR,SUMVAR))
                (X(1),A,COL(40),2(F(8,1)));
PUT SKIP FILE(OUT) EDIT('NET ANNUAL BENEFITS ($/ha)',
                       SUMPRF/N,SD(SSQPRF,SUMPRF))
                (X(1),A,COL(40),2(F(8,1)));
PUT SKIP FILE(OUT);
/*                                                                 */
/*+ + + + + + + + + + + + SD + + + + + + + + + + + + + + + + + + + +*/
/*                                                                 */
/* SD CALCULATES THE STANDARD DEVIATION                            */
/*                                                                 */
SD:PROCEDURE(SSQ,SUM);
DCL (SSQ,SUM) FLOAT;                 /* ASSUME N-1 WEIGHTING */
NN=N-1;
IF N < 2 THEN RETURN(0.0);
IF N > 29 THEN NN=N;                /* BIG SAMPLE USE N WEIGHTING   */
RETURN(SQRT((SSQ-SUM*SUM/N)/NN));
END SD;
/*                                                                 */
/*+ + + + + + + + + + + END OF SD + + + + + + + + + + + + + + + +  */
/*                                                                 */
END SUMRIZ;
/*                                                                 */
/**********************END OF SUMRIZ*******************************/
/*                                                                 */
/*                                                                 */
END IRRSIM;
/*                                                                 */
/*  THATHATHAT'S ALL FOLKS                                         */
/*                                                                 */
```

Appendix C Example Program Output

File OUT

```
                               SUMMARY

   LOCATION=CORONATION                        SOIL TYPE= I

   CROP=WHEAT   @ $180.00/t                   MANAGEMENT FACTOR= 0.75

   SPRING STARTING AVAILABLE MOISTURE    TOP                BOTTOM
        DRYLAND:                       0.50-1.00          0.25-1.00
        IRRIGATED:                     0.50-1.00          0.25-1.00

   IRRIGATED AREA=  32.0 ha                   SET AREA=  0.80 ha
   WATER SUPPLY FOR SEASON=  18286 ha-mm
            MAXIMUM TOTAL NET IRRIGATION=  400 mm

   SIDE ROLL                                  CAPACITY= .10.0 mm/h (NET)
   INTER SET MOVING TIME=0.70 h               SETS/d: MAX= 3.0  MIN= 3.0

    NO IRRIGATION BEFORE DAY = 150 OR AFTER DAY = 255

                                       IRRIGATION CRITERIA:
 LIFESTAGE    ROOT ZONE AM (mm)   MINIMUM AM (mm)   OPTIMUM AM (mm)
     1               36                 54                 70
     2               72                 70                 92
     3              108                 94                122
     4              144                 94                122
     5              144                 94                122

   FIXED SYSTEM COSTS= $127.34/ha             FERTILIZER COSTS= $ 33.00/ha
   VARIABLE COSTS= $0.4416/ha-mm              HARVESTING COSTS= $14.00/t

       SEED NUMBER= 246802


                   DRYLAND                         IRRIGATED
  YR  RAIN   SSM    ET   YIELD   SSM    IRR   #    ET   YIELD   VCOST  PROFIT
        mm    mm    mm   kg/ha    mm     mm         mm   kg/ha    $/ha    $/ha
 ----------------------------------------------------------------------------

   1   164    96   197    1429   129    219   3   328    2855   149.7   -20.3
   2   165   130   272    2134    84    246   4   358    3137   155.8  -102.6
   3   216   102   282    2330   100    219   3   380    3496   146.0   -63.5

                                    DRYLAND                IRRIGATED
                                MEAN        SD          MEAN        SD
                              ------------------------------------------

 OCT 15 SOIL MOISTURE (mm)        34        14           120        15
 TOTAL SURFACE RUNOFF (mm)         1         1             1         1
 DEEP PERCOLATION (mm)             2         4            32         4
 TOTAL ET (mm)                   362        40           468        22
 ANNUAL CROP ET (mm)             250        46           355        26
 ET/PET                         0.53      0.10          0.75      0.05
 YIELD (kg/ha)                  1964       474          3163       321


 IRRIGATION RESULTS                           MEAN      SD
 ---------------------------------------------------------

   YIELD INCREASE (kg/ha)                     1199     213
 NET APPLICATION (mm)                          228      16
   LABOUR (h)                                   96       6
   IRRIGATIONS/YEAR                           3.33    0.58
   TOTAL ANNUAL COSTS ($/ha)                 277.9     5.0
   NET ANNUAL BENEFITS ($/ha)                -62.1    41.2
```

File OYR with Daily Data

```
                    SEED NUMBER=246802          YEAR=  1

           CROP: WHEAT             WAGENINGEN METHOD

                                     DRYLAND                  IRRIGATED
DAY RAIN  PET PHENO-     SM    ET    YIELD   AREA  WATER       SM   ET     YIELD
    (mm) (mm) STAGE    (mm)  (mm)  (kg/ha)   (ha) (mm/ha)    (mm) (mm)  (kg/ha)
--------------------------------------------------------------------------------

 99  0.0  4.3  0.00    92.5   3.1       0     0.0     0.0   125.5  3.1        0
100  0.0  4.7  0.00    89.6   2.9       0     0.0     0.0   122.7  2.9        0
101  0.0  6.0  0.00    87.6   2.0       0     0.0     0.0   120.7  2.0        0
102  0.0  2.6  0.00    86.8   0.8       0     0.0     0.0   119.8  0.8        0
103  0.0  3.2  0.00    86.2   0.6       0     0.0     0.0   119.2  0.6        0
104  0.0  4.4  0.00    85.5   0.7       0     0.0     0.0   118.5  0.7        0
105  0.0  2.8  0.00    84.9   0.5       0     0.0     0.0   118.0  0.5        0
106  0.0  2.2  0.00    84.5   0.4       0     0.0     0.0   117.5  0.4        0
107  0.0  2.4  0.00    84.0   0.5       0     0.0     0.0   117.1  0.5        0
108  0.0  2.8  0.00    83.5   0.5       0     0.0     0.0   116.6  0.5        0
109  0.0  6.6  0.00    82.9   0.7       0     0.0     0.0   115.9  0.7        0
110  0.0  1.0  0.00    82.6   0.2       0     0.0     0.0   115.7  0.2        0
111  0.0  0.4  0.00    82.6   0.1       0     0.0     0.0   115.6  0.1        0
112  4.3  3.0  0.00    86.4   0.5       0     0.0     0.0   119.4  0.5        0
113  0.8  2.4  0.00    85.4   1.8       0     0.0     0.0   118.4  1.8        0
114  0.0  2.0  0.00    83.8   1.6       0     0.0     0.0   116.8  1.6        0
115  0.0  2.3  0.00    82.1   1.7       0     0.0     0.0   115.1  1.7        0
116  0.0  4.6  0.00    80.7   1.4       0     0.0     0.0   113.6  1.5        0
117  0.0  2.7  0.00    80.2   0.4       0     0.0     0.0   113.2  0.4        0
118  0.0  2.8  0.00    79.9   0.4       0     0.0     0.0   112.9  0.4        0
119  0.0  4.2  0.00    79.5   0.4       0     0.0     0.0   112.4  0.4        0
120  0.0  5.6  0.00    79.1   0.4       0     0.0     0.0   112.0  0.4        0
121  0.0  6.1  0.00    78.7   0.4       0     0.0     0.0   111.6  0.4        0
122  0.9  4.6  0.00    79.2   0.3       0     0.0     0.0   112.1  0.4        0
123  0.0  5.2  0.00    78.1   1.2       0     0.0     0.0   111.0  1.2        0
124  0.0  3.2  0.00    77.8   0.3       0     0.0     0.0   110.6  0.3        0
125  0.0  4.5  0.00    77.5   0.3       0     0.0     0.0   110.3  0.3        0
126  0.0  7.3  0.00    77.2   0.3       0     0.0     0.0   110.0  0.3        0
127  0.0  4.1  0.00    76.9   0.3       0     0.0     0.0   109.8  0.3        0
128  0.0  3.9  0.00    76.7   0.2       0     0.0     0.0   109.5  0.2        0
129  1.3  2.6  0.00    77.3   0.7       0     0.0     0.0   110.1  0.7        0
130  8.8  3.9  0.12    84.4   1.7       0     0.0     0.0   117.2  1.8        0
131  0.0  5.6  0.32    80.8   3.6       0     0.0     0.0   113.4  3.7        0
132  0.0  3.8  0.32    78.2   2.6       0     0.0     0.0   110.7  2.7        0
133  0.0  2.8  0.39    76.1   2.1       0     0.0     0.0   108.6  2.1        0
134  0.0  4.8  0.52    73.8   2.3       0     0.0     0.0   106.1  2.5        0
135  0.0  5.0  0.64    71.9   1.9       0     0.0     0.0   104.2  2.0        0
136  0.0  3.1  0.77    70.6   1.3       0     0.0     0.0   102.8  1.4        0
137  0.0  6.5  0.93    69.5   1.1       0     0.0     0.0   101.4  1.3        0
138  0.0  4.5  1.03    68.1   1.3       1     0.0     0.0   100.0  1.5        1
139  0.0  3.3  1.05    67.0   1.1       2     0.0     0.0    98.8  1.2        2
140  0.0  4.5  1.09    65.8   1.2       4     0.0     0.0    97.4  1.4        5
141  0.4  3.1  1.13    64.6   1.6       7     0.0     0.0    96.8  1.0        7
142  0.0  7.2  1.17    62.4   2.1      13     0.0     0.0    95.1  1.7       11
143  2.6  6.9  1.22    63.1   2.0      19     0.0     0.0    96.1  1.6       16
144  0.0  5.6  1.24    60.7   2.4      25     0.0     0.0    93.4  2.7       23
145  0.0  6.0  1.27    59.0   1.7      30     0.0     0.0    91.4  2.0       28
146  2.8  4.4  1.32    59.8   2.0      38     0.0     0.0    92.7  1.5       34
147  0.0  1.7  1.32    58.4   1.4      38     0.0     0.0    91.2  1.5       34
148  0.0  4.8  1.36    56.4   2.0      46     0.0     0.0    89.0  2.2       44
149  0.0  3.3  1.40    54.4   2.0      55     0.0     0.0    87.5  1.5       51
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150	0.0	3.3	1.42	53.1	1.4	57	0.0	0.0	85.9	1.6	53
151	0.0	7.0	1.46	51.8	1.3	64	2.4	73.0	104.8	2.1	64
152	0.0	6.0	1.50	50.5	1.3	72	2.4	73.0	101.6	3.2	83
153	0.3	6.4	1.56	49.5	1.2	81	2.4	73.0	98.6	3.2	107
154	0.0	6.5	1.60	48.1	1.4	90	2.4	73.0	95.7	2.9	127
155	4.0	4.9	1.64	50.9	1.2	99	2.4	73.0	97.5	2.2	142
156	19.6	3.0	1.67	68.6	1.9	107	2.4	73.0	114.2	2.4	153
157	0.7	4.7	1.71	65.4	4.0	138	2.4	73.0	131.6	4.3	187
158	0.0	5.1	1.77	61.3	4.1	178	2.4	73.0	126.9	4.8	233
159	6.7	6.5	1.83	63.9	4.0	218	2.4	73.0	128.3	5.3	286
160	0.6	6.4	1.88	59.6	4.9	267	0.0	0.0	123.0	5.9	345
161	0.0	5.2	1.94	55.8	3.8	312	0.0	0.0	118.5	4.5	398
162	0.0	6.7	1.99	52.8	3.0	343	0.0	0.0	114.3	4.2	441
163	1.7	4.6	2.04	51.0	3.5	383	0.0	0.0	112.0	4.0	486
164	0.0	5.1	2.08	48.4	2.6	414	0.0	0.0	108.5	3.5	528
165	9.3	2.7	2.11	55.2	2.4	457	2.4	73.0	115.2	2.5	572
166	0.0	6.4	2.15	50.7	4.5	509	2.4	73.0	109.5	5.8	639
167	3.7	1.7	2.19	52.7	1.8	557	2.4	73.0	111.4	1.8	688
168	0.0	4.2	2.22	49.1	3.6	595	2.4	73.0	107.3	4.1	732
169	0.0	9.4	2.28	45.9	3.2	620	0.8	73.0	124.6	6.2	781
170	0.0	5.2	2.31	43.3	2.6	650	2.4	73.0	140.9	4.7	834
171	0.0	2.2	2.31	41.4	1.8	658	2.4	73.0	138.4	2.4	844
172	0.0	5.3	2.34	39.0	2.4	685	2.4	73.0	133.7	4.7	898
173	1.6	4.2	2.37	37.7	3.0	722	2.4	73.0	131.5	3.8	946
174	0.7	5.0	2.42	35.9	2.5	750	2.4	73.0	128.2	4.0	992
175	1.9	3.5	2.45	35.3	2.5	781	2.4	73.0	127.0	3.0	1030
176	1.5	4.9	2.49	33.7	3.2	821	2.4	73.0	145.4	4.2	1083
177	0.0	3.8	2.52	31.7	2.0	845	2.4	73.0	141.8	3.6	1124
178	0.4	4.4	2.57	30.2	1.8	869	2.4	73.0	138.6	3.6	1172
179	0.0	7.5	2.62	29.1	1.1	881	2.4	73.0	133.5	5.0	1227
180	0.0	4.9	2.66	27.9	1.3	895	2.4	73.0	130.2	3.3	1265
181	0.0	6.6	2.71	26.8	1.1	907	2.4	73.0	126.6	3.6	1305
182	0.0	4.4	2.74	25.6	1.2	920	2.4	73.0	124.0	2.6	1334
183	0.3	4.5	2.77	24.5	1.3	937	0.8	73.0	142.3	2.9	1370
184	0.3	5.0	2.80	23.5	1.3	952	0.0	0.0	138.9	3.7	1415
185	0.0	5.8	2.85	22.4	1.0	964	0.0	0.0	134.9	3.9	1460
186	0.0	6.1	2.90	21.5	0.9	975	0.0	0.0	131.3	3.7	1503
187	0.0	4.7	2.92	20.5	1.0	987	0.0	0.0	128.4	2.8	1538
188	0.0	6.8	2.98	19.8	0.7	996	0.0	0.0	125.2	3.2	1576
189	0.0	8.1	3.02	19.0	0.7	982	0.0	0.0	120.8	4.5	1608
190	7.5	4.7	3.06	23.9	2.6	1001	0.0	0.0	124.6	3.6	1641
191	0.3	4.9	3.10	21.6	2.5	1019	0.0	0.0	120.2	4.7	1696
192	17.4	5.6	3.15	35.5	3.5	1050	0.0	0.0	132.5	5.0	1752
193	0.0	3.9	3.20	32.1	3.4	1087	0.0	0.0	127.7	4.8	1819
194	0.0	7.3	3.26	26.9	5.2	1133	0.0	0.0	119.7	8.1	1906
195	0.0	6.0	3.31	23.3	3.6	1163	0.0	0.0	113.9	5.7	1972
196	0.0	6.0	3.34	20.7	2.7	1176	0.0	0.0	109.1	4.8	2019
197	0.0	5.7	3.40	18.6	2.1	1178	0.0	0.0	105.0	4.1	2047
198	0.0	5.6	3.44	16.9	1.7	1178	0.0	0.0	101.3	3.6	2072
199	0.0	5.4	3.49	15.6	1.3	1171	0.0	0.0	98.3	3.1	2086
200	0.0	4.3	3.53	13.9	1.7	1185	2.4	73.0	117.9	3.0	2115
201	1.7	4.5	3.57	13.0	2.6	1209	2.4	73.0	115.6	3.9	2157
202	0.0	6.8	3.63	12.1	0.9	1208	2.4	73.0	110.2	5.4	2193
203	0.0	5.8	3.68	11.1	1.0	1212	2.4	73.0	105.7	4.5	2232
204	8.3	6.6	3.73	17.1	2.3	1228	2.4	73.0	109.0	4.9	2276
205	0.3	4.4	3.77	14.9	2.4	1250	2.4	73.0	104.9	4.4	2326
206	3.7	4.0	3.81	16.0	2.7	1276	2.4	73.0	127.3	4.0	2370
207	2.9	5.1	3.85	15.6	3.2	1306	2.4	73.0	124.7	5.4	2431
208	0.3	4.5	3.89	13.4	2.5	1325	2.4	73.0	120.0	5.0	2481
209	0.0	5.8	3.95	11.3	2.1	1337	2.4	73.0	114.3	5.6	2527

210	2.5	2.9	3.98	11.6	2.1	1360	2.4	73.0	113.6	3.2	2567
211	0.0	4.5	4.02	10.0	1.6	1368	2.4	73.0	110.0	3.6	2595
212	0.3	5.8	4.10	8.9	1.3	1375	2.4	73.0	106.8	3.5	2626
213	0.0	3.3	4.17	8.1	0.9	1380	0.8	73.0	126.9	2.9	2656
214	0.0	4.4	4.22	7.6	0.4	1377	0.0	0.0	123.5	3.4	2683
215	0.0	5.8	4.27	7.4	0.2	1373	0.0	0.0	119.6	3.8	2712
216	0.0	3.3	4.34	7.1	0.3	1369	0.0	0.0	117.3	2.4	2729
217	0.0	4.0	4.44	6.8	0.3	1366	0.0	0.0	114.7	2.5	2744
218	3.7	2.7	4.46	9.0	1.5	1372	0.0	0.0	116.2	2.2	2756
219	0.0	6.2	4.55	7.9	1.1	1382	0.0	0.0	112.3	3.9	2784
220	0.0	1.0	4.59	7.3	0.6	1395	0.0	0.0	111.2	1.0	2806
221	0.0	6.9	4.71	6.8	0.5	1399	0.0	0.0	108.1	3.1	2819
222	15.8	5.2	4.78	20.1	2.4	1411	0.0	0.0	120.2	3.6	2835
223	13.9	5.2	4.89	30.0	4.0	1421	0.0	0.0	128.7	5.1	2847
224	2.3	3.9	4.95	28.9	3.4	1429	0.0	0.0	127.0	4.1	2855
225	15.8	6.5	5.05	40.0	4.7	1429	0.0	0.0	137.2	4.8	2855
226	0.0	4.3	5.05	36.8	3.3	1429	0.0	0.0	133.9	3.3	2855
227	0.0	1.7	5.05	35.4	1.4	1429	0.0	0.0	132.6	1.4	2855
228	0.0	7.9	5.05	31.3	4.1	1429	0.0	0.0	128.4	4.2	2855
229	0.0	1.5	5.05	30.2	1.1	1429	0.0	0.0	127.3	1.1	2855
230	0.0	3.7	5.05	29.2	1.0	1429	0.0	0.0	126.3	1.0	2855
231	0.0	5.7	5.05	28.2	1.0	1429	0.0	0.0	125.3	1.0	2855
232	0.0	4.7	5.05	27.4	0.8	1429	0.0	0.0	124.5	0.8	2855
233	0.6	2.5	5.05	27.5	0.5	1429	0.0	0.0	124.6	0.5	2855
234	27.8	0.7	5.05	54.2	0.5	1429	0.0	0.0	146.9	0.5	2855
235	0.0	5.0	5.05	50.4	3.8	1429	0.0	0.0	143.1	3.8	2855
236	0.0	3.9	5.05	47.7	2.8	1429	0.0	0.0	140.3	2.8	2855
237	0.0	2.3	5.05	45.9	1.8	1429	0.0	0.0	138.6	1.8	2855
238	0.0	6.4	5.05	43.9	1.9	1429	0.0	0.0	136.6	1.9	2855
239	0.0	4.5	5.05	42.8	1.1	1429	0.0	0.0	135.5	1.1	2855
240	0.0	6.2	5.05	41.8	1.1	1429	0.0	0.0	134.4	1.1	2855
241	0.3	1.7	5.05	41.7	0.3	1429	0.0	0.0	134.3	0.3	2855
242	0.0	5.0	5.05	40.6	1.1	1429	0.0	0.0	133.2	1.1	2855
243	0.0	1.9	5.05	40.2	0.4	1429	0.0	0.0	132.9	0.4	2855
244	0.0	3.8	5.05	39.5	0.7	1429	0.0	0.0	132.2	0.7	2855
245	0.0	5.8	5.05	38.7	0.8	1429	0.0	0.0	131.3	0.8	2855
246	0.0	6.0	5.05	37.9	0.8	1429	0.0	0.0	130.5	0.8	2855
247	0.0	1.1	5.05	37.6	0.2	1429	0.0	0.0	130.3	0.2	2855
248	3.5	1.8	5.05	40.7	0.4	1429	0.0	0.0	133.4	0.4	2855
249	7.6	0.5	5.05	47.9	0.4	1429	0.0	0.0	140.5	0.4	2855
250	0.0	2.2	5.05	46.2	1.7	1429	0.0	0.0	138.8	1.7	2855
251	0.0	2.0	5.05	44.6	1.6	1429	0.0	0.0	137.2	1.6	2855
252	0.0	7.7	5.05	40.0	4.6	1429	0.0	0.0	132.6	4.6	2855
253	0.0	2.7	5.05	38.5	1.5	1429	0.0	0.0	131.0	1.5	2855
254	9.8	1.1	5.05	47.8	0.4	1429	0.0	0.0	140.3	0.4	2855
255	0.0	5.0	5.05	44.2	3.7	1429	0.0	0.0	136.7	3.7	2855
256	3.4	0.0	5.05	47.5	0.0	1429	0.0	0.0	140.0	0.0	2855
257	0.3	3.2	5.05	45.3	2.5	1429	0.0	0.0	137.8	2.5	2855
258	0.5	2.6	5.05	43.7	2.1	1429	0.0	0.0	136.2	2.1	2855
259	0.3	0.6	5.05	43.5	0.5	1429	0.0	0.0	135.9	0.5	2855
260	5.9	3.7	5.05	46.8	2.5	1429	0.0	0.0	139.2	2.5	2855
261	2.9	1.1	5.05	48.8	0.9	1429	0.0	0.0	141.2	0.9	2855
262	0.0	3.3	5.05	46.3	2.6	1429	0.0	0.0	138.6	2.6	2855
263	0.0	2.3	5.05	44.4	1.9	1429	0.0	0.0	136.8	1.9	2855
264	0.0	3.9	5.05	41.7	2.7	1429	0.0	0.0	134.1	2.7	2855
265	2.8	4.4	5.05	42.4	2.2	1429	0.0	0.0	134.7	2.2	2855
266	27.3	1.2	5.05	67.4	1.0	1429	0.0	0.0	151.9	1.0	2855
267	0.0	2.3	5.05	65.5	1.8	1429	0.0	0.0	150.1	1.8	2855
268	0.0	2.7	5.05	63.4	2.1	1429	0.0	0.0	148.0	2.1	2855
269	0.0	4.1	5.05	60.5	2.9	1429	0.0	0.0	145.1	2.9	2855

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270  0.0  3.1  5.05   58.5  2.0   1429    0.0    0.0  143.1  2.0   2855
271  0.0  1.2  5.05   57.6  0.9   1429    0.0    0.0  142.2  0.9   2855
272  0.0  3.9  5.05   56.8  0.8   1429    0.0    0.0  141.4  0.8   2855
273  0.0  2.3  5.05   56.4  0.5   1429    0.0    0.0  140.9  0.5   2855
274  0.0  2.0  5.05   56.0  0.4   1429    0.0    0.0  140.5  0.4   2855
275  0.0  5.3  5.05   55.0  0.9   1429    0.0    0.0  139.6  0.9   2855
276  0.0  4.3  5.05   54.3  0.8   1429    0.0    0.0  138.8  0.8   2855
277  1.4  1.0  5.05   55.5  0.2   1429    0.0    0.0  140.0  0.2   2855
278  0.0  1.9  5.05   54.1  1.3   1429    0.0    0.0  138.7  1.3   2855
279  0.0  3.2  5.05   53.1  1.0   1429    0.0    0.0  137.7  1.0   2855
280  0.0  5.1  5.05   52.3  0.8   1429    0.0    0.0  136.9  0.8   2855
281  0.0  2.2  5.05   51.9  0.4   1429    0.0    0.0  136.4  0.4   2855
282  6.2  1.8  5.05   57.7  0.4   1429    0.0    0.0  142.3  0.4   2855
283  1.1  2.3  5.05   57.0  1.8   1429    0.0    0.0  141.5  1.8   2855
284  0.0  5.1  5.05   53.5  3.4   1429    0.0    0.0  138.1  3.4   2855
285  0.0  0.0  5.05   53.5  0.0   1429    0.0    0.0  138.1  0.0   2855
286  0.0  3.7  5.05   51.3  2.3   1429    0.0    0.0  135.8  2.3   2855
287  0.0  1.9  5.05   50.0  1.3   1429    0.0    0.0  134.5  1.3   2855
288  0.0  0.4  5.05   49.8  0.2   1429    0.0    0.0  134.3  0.2   2855

    SOIL MOISTURE
          APRIL 9:              DRYLAND=  96 mm           IRRIGATED= 129 mm
          OCT 15:               DRYLAND=  50 mm           IRRIGATED= 134 mm

    TOTAL PRECIPITATION APRIL 9 TO OCT 15= 273 mm
    PRECIPITATION DURING ACTIVE GROWING SEASON= 164 mm

    TOTAL ET FROM APRIL 9 TO OCT 15
          DRYLAND= 317 mm
          IRRIGATED= 448 mm

    TOTAL SURFACE RUNOFF
          DRYLAND=   2 mm
          IRRIGATED=   2 mm

    TOTAL DEEP PERCOLATION
    DRYLAND=   0 mm
    IRRIGATED=  37 mm
    DEGREE DAYS ( > 5C ) DURING ACTIVE GROWING SEASON=  1011
    GROWTH STARTED ON DAY= 129 AND CONTINUED FOR  96 d

    IRRIGATIONS
        NUMBER      DAY STARTED          AMOUNT mm

            1           151                 73.0
            2           170                 73.0
            3           200                 73.0

          NET APPLICATION DEPTH= 219 mm
          GROSS WATER USED=    10011 ha-mm
          LABOUR=  92 HOURS

    YIELDS
          DRYLAND= 1429 kg/ha
          IRRIGATED= 2855 kg/ha
          INCREASE= 1426 kg/ha
                 =$ 257/ha

    VARIABLE COST=$ 150/ha


    TOTAL COSTS=$ 277/ha

    NET BENEFIT=$ -20/ha
              =$  -648
```

File OUT

```
                            SUMMARY

   LOCATION=CORONATION                         SOIL TYPE= I

   CROP=ALFALFA @ $ 80.00/t                    MANAGEMENT FACTOR= 0.75
        YIELD ESTIMATION BY WAGENINGEN METHOD

   SPRING STARTING AVAILABLE MOISTURE     TOP                BOTTOM
        DRYLAND:                       0.10-1.00           0.00-0.50
        IRRIGATED:                     0.10-1.00           0.00-0.50

   IRRIGATED AREA= 106.0 ha                    SET AREA= 53.00 ha
   WATER SUPPLY FOR SEASON=  66250 ha-mm
             MAXIMUM TOTAL NET IRRIGATION=  500 mm

   CENTRE PIVOT                                CAPACITY= 115.7 L/s (GROSS)
   MINIMUM REVOLUTIONS/d= 0.50                 MAXIMUM REVOLUTIONS/d= 2.00

    NO IRRIGATION BEFORE DAY = 150 OR AFTER DAY = 255


                                      IRRIGATION CRITERIA:
LIFESTAGE    ROOT ZONE AM (mm)   MINIMUM AM (mm)   OPTIMUM AM (mm)
    1             144                 72                 122
    2             192                 96                 163
    3             192                 96                 163
    4             192                 96                 163
    5             192                  0                   0

   FIXED SYSTEM COSTS= $169.81/ha              FERTILIZER COSTS= $ 46.00/ha
   VARIABLE COSTS= $0.4457/ha-mm               HARVESTING COSTS= $ 9.00/t

        SEED NUMBER= 987654


                    DRYLAND                      IRRIGATED
 YR RAIN  SSM  ET  YIELD(Kg/ha)  SSM IRR    #  ET   YIELD(Kg/ha)   VCOST   PROFIT
      mm   mm  mm   CUT1   CUT2   mm  mm       mm   CUT1   CUT2     $/ha     $/ha
_________________________________________________________________________________


  1 283   58 314   3513   2026   52 279    6 507   5487   4436    209.6    -28.7
  2 217   62 270   2628   1563   53 303    7 509   5266   4276    229.2     29.1
  3 309   36 294   3514   1481   55 271    6 496   5100   4141    205.1    -35.2
  4 242   64 281   3158   1687   97 241    6 530   5070   4267    193.7     -4.2
  5 298   63 354   2701   2585   18 271    6 533   4593   4326    199.6    -78.7
  6 270   56 315   2416   1625   47 269    5 545   4800   4218    210.6     17.8
  7 360   46 393   2856   3131   42 201    4 560   5010   4297    165.6    -69.8
  8 174   36 194   2018   1288   42 279    5 433   4468   3866    215.6     16.8
  9 303   49 303   2919   2350   55 243    5 484   4861   4489    190.8    -34.1
 10 237   29 202   1507      0   72 299    6 488   4821   4114    246.1    178.3
 11 291   22 288   2894      0   78 262    6 576   5796   3804    223.2    143.4
 12 228   56 251   2706      0   23 333    6 500   5035   4146    252.8     95.3
 13 250   84 303   2644   1254   79 291    6 544   5213   3983    223.5     30.5
 14 245   38 281   2866   1468   47 300    6 541   5397   4224    227.2     26.0
 15 213   92 292   2469   2018   87 278    5 550   4971   4228    212.4     -5.2
 16 239   75 285   3107   1264   58 295    6 523   5263   4200    223.1     14.5
```

```
17 273    73 339  3672  2237   46 225   5 523   5155  4034  175.9  -83.3
18 265    49 302  3452  1499   72 256   6 566   5459  4347  203.9   14.7
19 267    85 326  3309  1945   61 268   5 532   5050  4694  205.9  -16.5
20 255   106 339  4077  1855   83 240   5 528   5151  4261  184.3  -75.8
21 223    77 264  1557  1989   50 299   6 501   4189  4177  222.7   -6.9
22 221    92 296  2631  1713  100 289   6 549   4840  4752  222.3   27.8
23 195    64 236  2315     0   64 289   6 513   4627  3799  229.7   89.4
24 251    38 303  2408  2570   87 219   5 522   4967  4476  183.8    3.5
25 149    87 224  2112  1112   92 267   5 492   4510  3918  211.9   34.6

                                     DRYLAND           IRRIGATED
                                  MEAN      SD       MEAN      SD
                                 ______________________________________

OCT 15 SOIL MOISTURE (mm)          10       12         47      30
TOTAL SURFACE RUNOFF (mm)           1        1          1       2
DEEP PERCOLATION (mm)               0        0          2       1
TOTAL ET (mm)                     338       43        571      26
ANNUAL CROP ET (mm)               290       46        522      31
ET/PET                           0.45     0.07       0.82    0.05
YIELD (kg/ha)                    4324     1179       9223     449
    FIRST CUT=                   2778      625       5004     359
    SECOND CUT=                  1546      835       4219     243

IRRIGATION RESULTS                      MEAN      SD
_____________________________________________________

 YIELD INCREASE (kg/ha)                 4898    1022
NET APPLICATION (mm)                     271      30
 LABOUR (h)                               80      11
 IRRIGATIONS/YEAR                       5.60    0.65
 TOTAL ANNUAL COSTS ($/ha)             380.5    20.8
 NET ANNUAL BENEFITS ($/ha)             11.3    64.2
```

File OYR without Daily Data

```
                SEED NUMBER=987654          YEAR=  1
        CROP: ALFALFA           WAGENINGEN METHOD

        SOIL MOISTURE
             APRIL 9:                 DRYLAND=  58 mm               IRRIGATED=  52 mm
             OCT 15:                  DRYLAND=  27 mm               IRRIGATED= 101 mm
        TOTAL PRECIPITATION APRIL 9 TO OCT 15= 372 mm
        PRECIPITATION DURING ACTIVE GROWING SEASON= 283 mm

        TOTAL ET FROM APRIL 9 TO OCT 15
              DRYLAND= 399 mm
              IRRIGATED= 593 mm

        TOTAL SURFACE RUNOFF
              DRYLAND=    4 mm
              IRRIGATED=    4 mm

        TOTAL DEEP PERCOLATION
        DRYLAND=    0 mm
        IRRIGATED=    4 mm
        DEGREE DAYS ( > 5C ) DURING ACTIVE GROWING SEASON=  1183
        GROWTH STARTED ON DAY= 123 AND CONTINUED FOR 132 d

        IRRIGATIONS
            NUMBER       DAY STARTED          AMOUNT mm              FIELD
              1              151                111.6                  1
              2              163                139.9                  2
              3              181                 82.8                  1
              4              199                 78.0                  2
              5              210                 74.3                  1
              6              220                 70.6                  2
             NET APPLICATION DEPTH= 279 mm
             GROSS WATER USED=    36918 ha-mm
             LABOUR=  90 HOURS

        YIELDS
             DRYLAND= 5539 kg/ha
             IRRIGATED= 9924 kg/ha
             INCREASE= 4385 kg/ha
                      =$ 351/ha

        VARIABLE COST=$ 210/ha
        TOTAL COSTS=$ 379/ha

        NET BENEFIT=$ -29/ha
                   =$ -3039
                SEED NUMBER=197721          YEAR=  2
CROP: ALFALFA          WAGENINGEN METHOD

SOIL MOISTURE
      APRIL 9:              DRYLAND=  62 mm           IRRIGATED=  53 mm
      OCT 15:               DRYLAND=   0 mm           IRRIGATED=  51 mm

TOTAL PRECIPITATION APRIL 9 TO OCT 15= 278 mm
PRECIPITATION DURING ACTIVE GROWING SEASON= 217 mm

TOTAL ET FROM APRIL 9 TO OCT 15
      DRYLAND= 340 mm
      IRRIGATED= 582 mm

TOTAL SURFACE RUNOFF
      DRYLAND=    0 mm
      IRRIGATED=   0 mm

TOTAL DEEP PERCOLATION
DRYLAND=    0 mm
IRRIGATED=   2 mm
DEGREE DAYS ( > 5C ) DURING ACTIVE GROWING SEASON=  1189
GROWTH STARTED ON DAY= 129 AND CONTINUED FOR 127 d

IRRIGATIONS
   NUMBER      DAY STARTED          AMOUNT mm          FIELD
      1            151                86.9               1
      2            162               129.7               2
      3            174                88.1               1
      4            184                76.5               2
      5            200                79.3               1
      6            212                68.0               2
      7            220                77.4               1

      NET APPLICATION DEPTH= 303 mm
      GROSS WATER USED=    40139 ha-mm
      LABOUR= 104 HOURS

YIELDS
      DRYLAND= 4191 Kg/ha
      IRRIGATED= 9542 Kg/ha
      INCREASE= 5351 Kg/ha
               =$ 428/ha

VARIABLE COST=$ 229/ha
TOTAL COSTS=$ 399/ha

NET BENEFIT=$  29/ha
           =$  3084
```

```
                SEED NUMBER=   541          YEAR=  3

CROP: ALFALFA           WAGENINGEN METHOD

SOIL MOISTURE
      APRIL 9:              DRYLAND=  36 mm             IRRIGATED=  55 mm
      OCT 15:               DRYLAND=  37 mm             IRRIGATED= 122 mm

TOTAL PRECIPITATION APRIL 9 TO OCT 15= 371 mm
PRECIPITATION DURING ACTIVE GROWING SEASON= 309 mm

TOTAL ET FROM APRIL 9 TO OCT 15
      DRYLAND= 370 mm
      IRRIGATED= 573 mm

TOTAL SURFACE RUNOFF
      DRYLAND=   0 mm
      IRRIGATED=   0 mm

TOTAL DEEP PERCOLATION
DRYLAND=   0 mm
IRRIGATED=   3 mm
DEGREE DAYS ( > 5C ) DURING ACTIVE GROWING SEASON=  1170
GROWTH STARTED ON DAY= 119 AND CONTINUED FOR 134 d

IRRIGATIONS
    NUMBER      DAY STARTED          AMOUNT mm            FIELD
       1            151                 84.1                1
       2            172                 72.1                1
       3            181                140.4                2
       4            200                 69.3                2
       5            209                104.2                1
       6            221                 72.2                2

       NET APPLICATION DEPTH= 271 mm
       GROSS WATER USED=    35925 ha-mm
       LABOUR=  68 HOURS

YIELDS
       DRYLAND= 4996 kg/ha
       IRRIGATED= 9241 kg/ha
       INCREASE= 4245 kg/ha
               =$ 340/ha

VARIABLE COST=$ 205/ha
TOTAL COSTS=$ 375/ha

NET BENEFIT=$ -35/ha
           =$ -3736
```

Appendix D Precipitation Statistics

Nomenclature

AVG	average of the cube root of daily precipitation in millimeteres.
SD	standard deviation of the cube root of daily precipitation.
P(W/D)	probability of a wet day following a dry day.
P(W/W)	probability of a wet day following a wet day.

CORONATION

PERIOD	AVG	SD	P(W/D)	P(W/W)
1	1.26738	0.52261	0.20478	0.27273
2	1.31578	0.51736	0.17844	0.50495
3	1.50077	0.57578	0.16495	0.47312
4	1.35456	0.56890	0.22569	0.42157
5	1.41531	0.54408	0.21277	0.43519
6	1.40088	0.60844	0.26275	0.49630
7	1.43578	0.63125	0.30469	0.46269
8	1.43884	0.63975	0.30085	0.55844
9	1.55507	0.64713	0.30568	0.52795
10	1.62492	0.69701	0.28514	0.48227
11	1.52177	0.69779	0.30502	0.40458
12	1.55293	0.64498	0.31452	0.45775
13	1.51917	0.66601	0.23875	0.30693
14	1.52789	0.64734	0.20290	0.49123
15	1.43587	0.62078	0.21127	0.44340
16	1.39002	0.56164	0.18213	0.48485
17	1.51356	0.62569	0.17073	0.48544
18	1.36269	0.56672	0.17940	0.34831
19	1.22135	0.48385	0.12037	0.40909

EDMONTON

PERIOD	AVG	SD	P(W/D)	P(W/W)
1	1.33021	0.50794	0.21341	0.37500
2	1.22545	0.50493	0.16000	0.44444
3	1.31892	0.57190	0.18125	0.46667
4	1.38083	0.61692	0.21302	0.45455
5	1.44605	0.57277	0.23684	0.50667
6	1.42810	0.63540	0.24832	0.45570
7	1.48430	0.65098	0.37857	0.51765
8	1.58187	0.72850	0.32813	0.57143
9	1.75228	0.75944	0.35652	0.56604
10	1.64597	0.74925	0.39370	0.48387
11	1.47378	0.72163	0.37500	0.53000
12	1.60118	0.67067	0.42017	0.51923
13	1.52096	0.65535	0.31690	0.48780
14	1.44805	0.61343	0.26389	0.50617
15	1.55456	0.69355	0.34884	0.50538
16	1.47300	0.60806	0.26761	0.51282
17	1.42262	0.55593	0.23333	0.48571
18	1.29031	0.51831	0.19255	0.40678
19	1.21039	0.50011	0.14045	0.38095

LACOMBE

PERIOD	AVG	SD	P(W/D)	P(W/W)
1	1.34724	0.53506	0.19113	0.33537
2	1.33537	0.58146	0.17575	0.44886
3	1.46944	0.66018	0.18728	0.42857
4	1.48398	0.59236	0.21869	0.49302
5	1.52188	0.60975	0.29960	0.40945
6	1.56322	0.67103	0.30819	0.49648
7	1.56946	0.68045	0.34419	0.55312
8	1.59635	0.65036	0.36451	0.54955
9	1.64232	0.66309	0.38931	0.57423
10	1.54087	0.67607	0.32751	0.47603
11	1.53417	0.64749	0.31466	0.47902
12	1.54851	0.68564	0.32294	0.53846
13	1.53784	0.63659	0.28151	0.44853
14	1.51001	0.66875	0.26707	0.51587
15	1.50587	0.63977	0.25852	0.44177
16	1.49550	0.58686	0.23077	0.48696
17	1.42864	0.57730	0.23896	0.49597
18	1.31205	0.49445	0.18635	0.43455
19	1.32896	0.50798	0.15835	0.30597

LETHBRIDGE

PERIOD	AVG	SD	P(W/D)	P(W/W)
1	1.40288	0.54592	0.16129	0.43704
2	1.52619	0.66635	0.21123	0.49359
3	1.38284	0.66093	0.23037	0.42568
4	1.51659	0.61994	0.22102	0.48428
5	1.48618	0.66489	0.23770	0.46341
6	1.58037	0.72645	0.30000	0.57619
7	1.61319	0.70655	0.26829	0.52475
8	1.62024	0.77422	0.27714	0.50000
9	1.52434	0.72481	0.27635	0.43017
10	1.43366	0.63634	0.19843	0.44898
11	1.48102	0.61656	0.14118	0.40952
12	1.42575	0.63529	0.17026	0.43363
13	1.47395	0.67247	0.17676	0.32479
14	1.49205	0.70607	0.17831	0.40000
15	1.51279	0.62275	0.18182	0.39837
16	1.51106	0.65360	0.19697	0.40299
17	1.55368	0.64625	0.18373	0.51007
18	1.40971	0.61078	0.15130	0.44860
19	1.26108	0.54130	0.15274	0.34234

Appendix E Temperature and PET Statistics

Nomenclature

PRD	Ten day period
WET	D -> dry day, W-> wet day
AVGTMAX	Average daily Maximum temperature (C)
SDTMAX	Standard deviation on daily maximum temperature (C)
ATXTN	Intercept of regression line of Tmin on Tmax
BTXTN	Slope of regression line of Tmin on Tmax
SETXTN	Standard error about regression line of Tmin on Tmax
ATXPET	Intercept of regression line of PET on Tmax
BTXPET	Slope of regression line of PET on Tmax
SETXPET	Standard error about regression line of PET on Tmax

CORONATION

PRD	WET	AVGTMAX	SDTMAX	ATXTN	BTXTN	SETXTN	ATXPET	BTXPET	SETXPET
1	D	9.6328	6.3210	-7.76122	0.49661	3.17839	1.18959	0.16096	0.7165
	W	4.9938	5.7032	-5.67853	0.42487	3.08589	1.09998	0.14873	0.7661
2	D	13.0734	6.6559	-6.85430	0.42494	2.81195	1.15968	0.18602	0.7093
	W	6.9283	6.9162	-4.85935	0.48837	2.65549	1.48321	0.13133	0.8899
3	D	15.2850	5.9255	-6.00129	0.45398	2.93831	1.15141	0.19979	0.7743
	W	10.3696	5.2327	-2.56796	0.37500	2.46335	0.90741	0.19566	0.7915
4	D	17.7652	4.9341	-4.75404	0.42128	2.85977	0.82377	0.22287	0.8587
	W	13.6824	5.6056	-0.65589	0.30794	2.53024	0.63453	0.22222	0.9730
5	D	19.6901	4.7695	-3.50520	0.42007	2.77190	0.45930	0.23589	0.7666
	W	16.6691	5.2617	-0.15441	0.34146	2.30104	1.15203	0.17691	0.8489
6	D	20.8387	5.3641	-3.22094	0.45027	2.74727	0.02685	0.24965	0.7938
	W	17.6552	4.8813	0.24536	0.39501	2.26336	-0.27662	0.23368	0.8264
7	D	21.4140	4.3555	-0.44224	0.36809	2.59926	-0.09966	0.23916	0.7390
	W	18.6136	4.7167	3.15167	0.26408	2.65997	-0.42371	0.24498	0.9170
8	D	22.7179	4.5473	-0.17305	0.35922	2.60324	-0.66075	0.26372	0.7722
	W	19.7204	4.6075	4.05186	0.22666	2.54423	-0.17913	0.22444	0.8202
9	D	24.0940	4.1616	0.04541	0.38257	2.37034	-0.07857	0.22287	0.7257
	W	20.3516	4.6892	3.62276	0.28457	2.24376	-0.35303	0.22451	0.8644
10	D	25.2195	4.0997	0.27841	0.40864	2.35157	-0.52348	0.24121	0.7663
	W	22.2108	4.2741	5.10156	0.25643	1.90668	-0.58016	0.22525	0.7277
11	D	25.5178	4.3028	1.11653	0.36933	2.29675	-1.14720	0.25225	0.6550
	W	22.7227	4.3979	5.43201	0.24834	2.13925	-1.93438	0.27465	0.7770
12	D	25.5291	4.3160	1.41398	0.34784	2.38791	-1.96421	0. 8100	0.7910
	W	22.0189	4.4493	6.83006	0.18884	2.03591	-1.01446	0.22768	0.9319
13	D	24.6927	4.5806	1.96923	0.30975	2.60213	-2.44239	0.29303	0.7901
	W	21.2240	5.1285	2.97284	0.31131	2.33068	-1.53938	0.25329	0.8747
14	D	23.9993	4.8863	-0.87560	0.39424	2.75476	-1.75918	0.26545	0.8111
	W	18.6616	5.0435	4.09554	0.23827	2.77990	-1.44284	0.23785	0.8880
15	D	21.6968	4.7636	0.18747	0.30799	2.75738	-1.32576	0.24568	0.7779
	W	16.3635	5.2780	1.03785	0.35322	2.39919	-0.06441	0.17068	1.1124
16	D	20.2944	5.3115	-1.90416	0.34869	3.36444	-0.16831	0.18875	0.7899
	W	13.4822	5.3413	-0.67476	0.39168	2.88898	0.19129	0.15611	0.8970
17	D	17.7395	6.2232	-2.69157	0.32297	3.08198	-0.20137	0.18760	0.7858
	W	11.1727	5.3947	-1.18464	0.36767	2.39694	0.15323	0.16652	1.0877
18	D	15.3121	6.4783	-5.36438	0.42903	3.26931	-0.21344	0.18708	0.7790
	W	9.3435	6.1018	-3.14685	0.43198	2.95174	0.25173	0.15265	0.8093
19	D	14.2037	6.3359	-5.55768	0.35856	3.24213	0.03235	0.16849	0.6892
	W	6.7939	5.8744	-4.52091	0.52516	2.71164	0.54691	0.08189	0.6911

EDMONTON

PRD	WET	AVGTMAX	SDTMAX	ATXTN	BTXTN	SETXTN	ATXPET	BTXPET	SETXPET
1	D	9.0164	5.6884	-6.91039	0.39030	2.93821	1.36310	0.13039	0.7534
	W	4.9839	5.6708	-5.70423	0.52073	3.08617	1.38390	0.11966	0.6216
2	D	13.4552	6.0522	-6.84219	0.42927	2.70433	1.37589	0.17137	0.7891
	W	9.0792	5.7281	-4.34785	0.42634	2.49830	1.46133	0.14460	0.9053
3	D	15.6294	5.2336	-4.16664	0.29148	2.83099	1.29721	0.19838	1.0035
	W	11.8552	5.1673	-1.79943	0.33285	2.41012	0.81878	0.19553	1.0281
4	D	17.9506	4.7810	-4.55782	0.35391	3.00788	0.94104	0.22496	0.9505
	W	14.2098	4.2991	-1.80805	0.32244	2.53699	0.20549	0.22827	0.9837
5	D	20.4806	4.4862	-4.27208	0.42415	2.81723	0.40828	0.25177	1.2745
	W	16.0486	4.4351	1.54785	0.25106	2.33656	-0.11897	0.25258	0.9823
6	D	21.7174	4.8248	-3.65394	0.42112	3.18578	0.73473	0.21628	0.9048
	W	17.3175	4.1105	2.02554	0.27047	2.65171	0.52670	0.20584	0.8382
7	D	21.5201	3.6718	-1.63421	0.38288	3.24584	0.34970	0.22661	0.8877
	W	18.8612	4.4483	3.48723	0.25068	3.04891	0.11318	0.20828	0.8413
8	D	22.5752	3.8126	-0.85676	0.35294	3.13228	0.85111	0.19930	0.7837
	W	19.5530	4.3977	4.82265	0.19313	2.50429	-0.97555	0.26094	0.9582
9	D	23.6859	3.9459	-3.00904	0.48255	2.74807	0.58683	0.19544	0.6807
	W	19.4020	4.2098	4.45898	0.22109	2.28784	0.48219	0.19004	0.9108
10	D	23.8624	3.2586	-1.06682	0.41989	2.47049	1.17629	0.17253	1.0587
	W	20.6137	3.8822	5.90256	0.21251	2.30744	-1.73745	0.26968	0.8363
11	D	23.9729	3.1219	-4.15649	0.53998	2.39130	0.38350	0.18900	0.7948
	W	20.6061	3.7151	4.13230	0.26178	2.48472	-0.88078	0.22529	0.6802
12	D	23.8741	3.5175	0.49139	0.37619	2.41609	0.53376	0.16915	0.7673
	W	21.1133	4.0680	7.35321	0.13271	2.40822	-0.94308	0.21881	0.7918
13	D	23.3514	4.2460	-3.92943	0.51735	2.66696	-0.26071	0.19676	0.6054
	W	21.0628	3.8713	-0.23702	0.44744	2.79056	-0.26027	0.17895	0.6278
14	D	22.5116	4.5364	-1.70969	0.39475	2.79497	-0.47472	0.19836	0.6907
	W	18.1741	4.2375	2.70516	0.25853	2.06255	-0.90297	0.19873	0.7350
15	D	20.9815	4.8005	-1.42285	0.34172	3.02509	-1.16272	0.22227	0.8120
	W	16.2140	4.1450	2.36726	0.23353	2.51747	-0.10019	0.15861	0.7326
16	D	19.2120	5.2319	-3.62038	0.38228	3.00284	0.14848	0.15041	0.8049
	W	12.9333	5.1222	-2.39551	0.51413	2.83404	0.49929	0.10565	0.6019
17	D	18.0523	5.9376	-3.05960	0.30240	2.78321	0.09745	0.13886	0.9108
	W	11.7725	4.9206	-0.94083	0.28920	2.94987	-0.14404	0.16725	0.8848
18	D	16.0194	6.1978	-5.16319	0.37221	2.87141	0.46468	0.11284	0.8483
	W	10.7073	4.1998	-1.43549	0.25344	2.64437	0.33041	0.09863	0.5340
19	D	13.9156	6.2458	-7.05916	0.43458	3.18761	0.23928	0.12097	0.8327
	W	8.9366	5.8951	-5.25544	0.46008	3.56361	0.29953	0.10001	0.4260

LACOMBE

PRD	WET	AVGTMAX	SDTMAX	ATXTN	BTXTN	SETXTN	ATXPET	BTXPET	SETXPET
1	D	11.2975	6.2581	-7.53727	0.35094	3.44833	1.52674	0.13355	0.7919
	W	7.0814	6.9288	-5.58908	0.40629	3.75574	1.25774	0.13951	0.6440
2	D	13.9869	6.0931	-6.41372	0.31791	3.21566	1.66922	0.15065	0.8656
	W	8.3089	6.5432	-4.56907	0.36890	3.37284	1.41317	0.16117	0.8295
3	D	16.1264	5.5529	-5.40858	0.31340	3.39861	1.42985	0.18541	1.0401
	W	11.4679	6.5360	-1.80522	0.27518	3.01440	0.95711	0.18479	0.7893
4	D	18.1512	5.1332	-2.83278	0.23933	3.29085	1.00178	0.22657	1.1736
	W	14.3363	5.2301	-0.06523	0.20849	2.79432	0.50330	0.22710	0.8700
5	D	20.2070	5.1520	-1.58412	0.24944	3.48194	1.26031	0.20962	1.1068
	W	15.7667	5.4309	0.56665	0.23784	3.35923	0.36522	0.23281	0.8441
6	D	20.3452	4.9460	-1.77163	0.29882	3.37039	1.22229	0.20725	1.0194
	W	17.2638	5.2812	2.43687	0.18926	3.24633	0.27318	0.22521	0.9746
7	D	22.1833	4.2412	-0.69518	0.29672	3.21836	0.81908	0.22202	1.0326
	W	19.0609	4.7986	4.31259	0.14299	3.13920	-0.21784	0.23462	0.9189
8	D	22.4951	4.3673	-0.06420	0.29945	3.18319	0.18019	0.24551	0.9213
	W	19.5292	4.8049	4.93002	0.14448	2.88826	-0.67905	0.26607	0.9841
9	D	23.8171	4.2245	3.24844	0.18386	3.09614	0.41007	0.21519	0.9239
	W	20.8620	4.4128	6.07902	0.11624	2.91327	0.01215	0.21774	0.9105
10	D	25.2006	4.1157	3.60653	0.18976	3.28013	-0.04867	0.22487	0.9685
	W	21.6526	4.2289	6.19394	0.13455	3.01547	-0.23107	0.21855	0.8338
11	D	25.6546	3.9181	1.97729	0.26782	2.91781	-0.10150	0.22088	0.7257
	W	22.5551	4.5710	5.25829	0.17568	2.75598	-0.55551	0.22818	0.6724
12	D	24.7388	3.9683	3.73791	0.18023	3.14176	0.37001	0.18572	0.8317
	W	21.8618	4.8019	7.81193	0.06339	3.00865	-0.76938	0.22403	0.7276
13	D	24.3401	4.3780	3.73408	0.14813	3.05798	0.08031	0.19124	0.7369
	W	20.9840	4.5520	6.63736	0.07532	3.03589	-0.56021	0.20587	0.6760
14	D	23.6825	4.3647	1.40705	0.20466	3.14142	0.20899	0.17724	0.6710
	W	19.3540	5.3869	5.16641	0.11757	2.91118	-0.38140	0.18236	0.7328
15	D	21.9411	5.0871	1.52080	0.15180	3.28860	0.57857	0.14329	0.6987
	W	17.2924	5.2730	4.95205	0.06082	3.10221	0.55709	0.13455	0.7790
16	D	20.2726	5.4742	-0.82267	0.18550	3.67379	0.81800	0.11654	0.7131
	W	15.0616	5.8089	1.58526	0.19484	3.34418	0.67848	0.12074	0.7188
17	D	18.6369	6.2554	-2.40172	0.19035	3.37191	0.57919	0.11458	0.7661
	W	12.0946	6.0814	-0.71790	0.24659	3.29233	0.54317	0.12257	0.6611
18	D	16.7798	6.5307	-3.79454	0.20027	3.56634	0.69735	0.11127	0.7852
	W	11.2810	6.4297	-1.91836	0.29348	3.10577	0.54826	0.10610	0.6807
19	D	14.8565	6.6950	-5.47690	0.23294	3.51124	0.48401	0.10469	0.8366
	W	9.8970	6.8091	-3.16358	0.30742	3.41630	0.67322	0.12537	0.7807

LETHBRIDGE

PRD	WET	AVGTMAX	SDTMAX	ATXTN	BTXTN	SETXTN	ATXPET	BTXPET	SETXPET
1	D	13.6250	6.1631	-8.08640	0.50277	3.63701	1.06	0.13355	0.7919
	W	7.4160	6.7528	-5.98305	0.50654	3.36694	1.06	0.13951	0.6440
2	D	14.7534	6.4988	-7.10523	0.47143	3.38153	1.69	0.15065	0.8656
	W	7.9487	5.8552	-4.17953	0.44203	2.72635	1.52	0.16117	0.8295
3	D	17.0565	5.5349	-4.77362	0.38661	3.22371	1.84	0.18541	1.0401
	W	11.5526	5.8120	-1.92159	0.35200	2.66706	1.33	0.18479	0.7893
4	D	19.3321	5.2660	-4.95836	0.44208	3.23596	1.91	0.22657	1.1736
	W	13.5779	6.0486	-0.95245	0.33572	2.62864	1.46	0.22710	0.8700
5	D	20.9612	4.9398	-3.17525	0.42201	2.87146	1.79	0.20962	1.1068
	W	16.4212	5.7715	-0.34317	0.38080	2.76301	1.08	0.23281	0.8441
6	D	21.6542	4.9739	-1.02095	0.37100	3.06747	1.91	0.20725	1.0194
	W	17.3758	5.5307	1.81420	0.29695	2.81755	1.28	0.22521	0.9746
7	D	22.7695	4.3996	0.37671	0.34254	2.72250	1.39	0.22202	1.0326
	W	18.8001	5.2784	3.15833	0.29232	2.32632	0.78	0.23462	0.9189
8	D	23.8387	4.4274	-0.30069	0.40316	2.56034	0.64	0.24551	0.9213
	W	19.8247	5.5371	3.16175	0.31017	2.34378	-0.07	0.26607	0.9841
9	D	25.3308	4.0079	0.35455	0.37480	2.45079	1.30	0.21519	0.9239
	W	21.6698	5.3195	3.62106	0.28361	2.28770	0.47	0.21774	0.9105
10	D	27.3783	3.9475	0.68090	0.37432	2.68225	0.83	0.22487	0.9685
	W	23.6111	4.7486	5.80344	0.23142	2.45283	0.03	0.21855	0.8338
11	D	28.1043	4.0090	1.15644	0.35758	2.64538	0.79	0.22088	0.7257
	W	23.5329	5.4831	5.95641	0.23692	2.17725	-0.16	0.22818	0.6724
12	D	27.6165	4.2517	0.46990	0.37286	2.71061	1.67	0.18572	0.8317
	W	23.8889	4.5174	5.39236	0.23106	2.39639	-0.35	0.22403	0.7276
13	D	26.9902	4.3364	2.55602	0.28514	2.62946	1.44	0.19124	0.7369
	W	22.2773	4.9792	5.58922	0.21013	2.51601	0.16	0.20587	0.6760
14	D	25.8550	4.5206	3.66813	0.21571	2.84029	1.07	0.17724	0.6710
	W	21.2315	5.7682	5.13621	0.21731	2.42266	0.44	0.18236	0.7328
15	D	24.1619	4.7940	0.06169	0.32890	2.82397	1.70	0.14329	0.6987
	W	18.3107	5.6033	3.54715	0.27347	2.82257	1.53	0.13455	0.7790
16	D	21.7448	5.5610	-1.41097	0.34766	3.38568	2.55	0.11654	0.7131
	W	16.1279	6.6156	-0.21289	0.39394	2.97818	2.01	0.12074	0.7188
17	D	19.9537	5.9929	-3.43175	0.39820	3.36578	2.70	0.11458	0.7661
	W	12.5380	7.5506	-1.73584	0.39004	3.00507	2.36	0.12257	0.6611
18	D	18.2934	6.2856	-3.97023	0.40215	3.83464	2.97	0.11127	0.7852
	W	10.9871	7.2073	-2.25576	0.43556	3.00748	2.73	0.10610	0.6807
19	D	16.3577	6.4365	-5.38647	0.43586	3.80796	3.11	0.10469	0.8366
	W	10.6699	6.8566	-3.53536	0.39566	3.09916	2.56	0.12537	0.7807

Appendix F Estimated PET

Daily PET (mm) Calculated from Historical Meteorologcal Data for Coronation

Ten Day Period	Dry Days		Wet Days	
	mean	SD	mean	SD
1	2.69	1.19	1.86	1.12
2	3.28	1.25	2.20	1.21
3	4.22	1.45	2.72	1.29
4	4.74	1.42	3.57	1.55
5	5.09	1.34	4.10	1.26
6	5.39	1.50	4.10	1.31
7	5.00	1.22	4.19	1.49
8	5.44	1.41	4.20	1.33
9	5.19	1.15	4.10	1.39
10	5.72	1.23	4.40	1.98
11	5.25	1.24	4.31	1.37
12	5.23	1.49	3.94	1.35
13	4.97	1.54	3.83	1.66
14	4.74	1.51	2.91	1.50
15	3.96	1.42	2.74	1.43
16	3.65	1.23	2.19	1.23
17	3.02	1.35	1.93	1.26
18	2.66	1.48	1.67	1.27
19	2.31	1.30	1.02	0.84

Daily PET (mm) Calculated from Historical Meteorological Data for Edmonton

Ten Day Period	Dry Days		Wet Days	
	mean	SD	mean	SD
1	2.54	1.66	1.98	0.92
2	3.68	1.30	2.77	1.22
3	4.40	1.44	3.10	1.41
4	4.99	1.41	3.45	1.38
5	5.62	1.69	3.93	1.49
6	5.43	1.39	4.07	1.19
7	5.23	1.22	4.05	1.25
8	5.38	1.08	4.13	1.50
9	5.22	1.63	4.17	1.21
10	5.29	1.20	3.82	1.34
11	4.91	0.98	3.76	1.08
12	4.58	0.97	3.67	1.19
13	4.35	1.03	3.51	0.94
14	4.01	1.12	2.71	1.13
15	3.54	1.31	2.48	0.99
16	3.04	1.12	1.87	0.81
17	2.60	1.23	1.82	1.20
18	2.27	1.10	1.38	0.67
19	1.92	1.12	1.20	0.72

Daily PET (mm) Calculated from Historical Meteorological Data for Lacombe

Ten Day Period	Dry Days mean	Dry Days SD	Wet Days mean	Wet Days SD
1	2.88	1.12	2.10	1.03
2	3.64	1.26	2.58	1.35
3	4.30	1.48	2.99	1.45
4	5.07	1.62	3.67	1.46
5	5.46	1.50	4.08	1.52
6	5.53	1.45	4.21	1.53
7	5.65	1.38	4.08	1.35
8	5.67	1.33	4.50	1.60
9	5.30	1.24	4.38	1.39
10	5.40	1.30	4.48	1.20
11	5.30	1.12	4.49	1.20
12	4.82	1.09	4.00	1.24
13	4.62	1.10	3.77	1.09
14	4.36	1.01	2.92	1.17
15	3.46	0.98	2.90	1.02
16	3.12	0.95	2.43	1.02
17	2.63	0.98	2.10	0.99
18	2.48	1.07	1.68	0.95
19	1.93	1.10	1.95	1.27

Daily PET (mm) Calculated by Weather Model for Lethbridge

Ten Day Period	Dry Days mean	Dry Days SD	Wet Days mean	Wet Days SD
1	2.93	1.16	2.05	1.08
2	3.99	1.34	2.82	1.26
3	5.09	1.49	3.57	1.26
4	6.27	1.76	4.47	1.77
5	6.14	1.49	5.06	1.55
6	6.37	1.53	5.00	1.57
7	6.53	1.35	5.30	1.52
8	6.27	1.54	5.28	1.73
9	6.84	1.26	5.16	1.48
10	6.85	1.33	5.20	1.22
11	7.13	1.09	4.99	1.48
12	6.70	1.09	5.14	1.22
13	6.65	1.06	4.71	1.20
14	5.65	0.98	4.38	1.29
15	5.11	1.00	4.04	1.10
16	5.10	0.97	3.89	1.08
17	5.00	1.00	3.93	1.24
18	4.94	1.05	3.96	0.96
19	4.93	1.09	3.90	1.23